ARS National Research Program

NRP NO. 20260 Biological agents for pest control

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Each of the ARS National Research Programs and Special Research Programs outlines a 10-year plan that describes current technology and new technology expected in the 10-year period. The plan includes approaches to research and benefits expected to result from new technology. The Special Research Programs facilitate research planning and management in those exceptional circumstances where special funds are involved or a different kind of research management is needed. They provide the same general type of information as the ARS-NRP's. Both types of research programs were prepared by the National Program Staff with the cooperation of Regional Staffs and Line Managers, Technical Advisors, Research Leaders, and other scientists.

These research plans will be used for a variety of purposes. They serve to link ARS research projects to major program areas involving several agencies within the USDA program structure. ARS-NRP's and ARS-SRP's identify important national problems and describe plans for achieving technological objectives. They provide justifications for current research activities and the basis for funds for future research. They serve as the basis for program reports and for the Agency's accounting system. They also improve the communication between scientists and management, between research managers and staff scientists, between ARS and other research organizations, and between USDA and other departments, the private sector, and Congress.

These documents are dynamic statements of ARS research plans and, as new knowledge is developed, they will be continually updated to reflect changes in objectives and research approaches.

ARS-NRP No: 20260
USDA Program: 22-677

BIOLOGICAL AGENTS FOR PEST CONTROL

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BIOLOGICAL AGENTS FOR PEST CONTROL

I INTRODUCTION

More than 20,000 pest species, including insects, weeds, nematodes, and pathogens, cause losses amounting to 12 billion dollars annually in the U.S. The discovery, importation, and utilization of natural enemies are important tools in effective management of agricultural pests, particularly in view of the current worldwide concern over food and energy supplies and the quality of the environment. One objective of this ARS National Research Program is the exploration, evaluation, importation, and establishment of exotic natural enemies of a wide variety of pests, primarily introduced species, affecting U.S. agricultural production. Another objective involves two additional aspects of biological control, namely, the augmentation and conservation of native and introduced natural enemies for control of agricultural pests. In addition, this NRP is concerned with the identification and classification of insects and mites as integrally related to pest management and to support Federal and State agencies and other institutions. This NRP supports all the other NRP's developing control strategies against pests and contributes directly to Program 677, Crop Production Efficiency Research, Operating Goal 2, New Knowledge to Increase Productivity, and USDA Mission 2, Agricultural Production Efficiency. It also contributes to several other Programs, Goals and Missions.

II ARS NATIONAL RESEARCH PROGRAM SUMMARY

A Current Technology. There are more than 10,000 insect pest species in the U.S. causing losses estimated to be more than 6 billion dollars. Of these, a recent compilation shows that 751 have been accidentally introduced into the U.S., including 249 of the 700 species classified as important agricultural, forestry, or horticultural pests. That is, about 35% of our important arthropod pests are of foreign origin. Moreover, despite our quarantine regulations, new alien pests of major importance are found in the U.S. at the rate of one every 3 years.

The importation of natural enemies represents a potentially inexpensive means of increasing production of food and fiber, without hazard to the environment, and with low energy expenditures. If successfully established, introduced natural enemies are self-perpetuating pest control agents, causing no environmental pollution, and if effective, the use of energy to produce and apply pesticides is reduced or in some cases eliminated. The same can be said concerning efforts to increase the effectiveness of natural enemies, both native and introduced, through methods of conservation and augmentation.

Conservation involves the judicious use of pesticides, if needed, or other methods of pest control, in ways calculated to interfere as little as possible with, or to actually assist the natural controlling action of the pest's natural enemies in order to obtain the needed degree of economic control of the pest, or pest complex in a crop system. Augmentation, as the term implies, means increasing the numbers of natural enemies, by means of laboratory culture or other field techniques, and often the application of these increased numbers at critical periods during the life history of the pest or period of crop development in order to increase the effectiveness of the natural enemies in controlling the pest. All three biological control approaches, importation, augmentation, and conservation, can be used alone or together, or be utilized together with other control measures in a totally integrated pest management program.

The identification of arthropods is the primary step in all pest control efforts. Without the proper identity of pest or beneficial species the chances for successful pest management are minimal. Hundreds of thousands of dollars have been wasted in pest control operations where species have been misidentified. Arthropod classification is the framework upon which identification rests. It is dynamic, continually evolving to reflect the research of all taxonomists as new species and new relationships between species are discovered.

The current state of the art in biological control is most advanced in the discovery, importation, and evaluation of insect biological agents which attack insects and weeds. A few recent successes include the control of the alfalfa weevil which is a major pest of the most important forage crop in the U.S. with parasites imported from Europe. Based on an average cost of $5 per acre for chemicals and labor, the savings resulting from reduction in treatment were calculated to be $224,000 for New Jersey alone in 1975. Savings due to reductions in acreage treated in 10 States, including New Jersey, were estimated to be over $5,000,000 in 1975. Control of musk thistle, an imported weed pest which infects 2 million acres of pasture, range, and croplands in certain areas from Idaho to Tennessee, with 2 weed-feeding insects introduced from Europe may produce a savings of $3,000,000 per year in control costs alone. Equally promising advances have been made utilizing native biological control agents. The control of northern joint-vetch, a serious pest of rice and soybeans in the southern U.S., with an indigenous fungus disease which kills the weed, has been proved more feasible than the use of hormonal herbicides such as 2,4,5-T, which have objectionable side effects on crop plants and warm-blooded animals. Based on losses of $5.7 million calculated from acres infested, average yields, prices and assigned percent losses (ARS-4-1, 1972; Research Report of S. Weed Sciences Soc. 1974) benefits from this bioagent have been estimated at $2.8 million dollars annually. ARS research on microbial insecticides has provided safe, effective alternatives to the use of chemical pesticides with the registration of a virus disease which controls the two major pests of corn and cotton, the corn earworm/cotton bollworm, and the tobacco budworm. The utilization of other insect diseases such as Bacillus thuringiensis in commercial pest control has increased from 25,000 pounds/year to 2 million pounds/year as a result of ARS research which has provided a more effective strain of the bacteria.

Accurate identification of pest and beneficial insects and mites is the keystone of pest control. Currently, about one million species of insects alone have been described. Those yet to be discovered and described have been estimated at 3-10 million. Only 40% of the species of major North American groups have been described. Highly competent taxonomists with the best literature and reference specimen resources can identify only about 41,000 of the 104,000 described North American species.

B Visualized Technology. In view of the increasing restrictions imposed by governmental agencies on the use of chemical pesticides, and the increasing chemical resistance in insects, it is reasonable to assume that pest control in the future will depend upon biological agents to greater extent than ever before. In the next 10 years new parasites and predators will be discovered, introduced and established for control of such plant feeding insects as cotton bollworms, lygus bugs, gypsy moths, and greenbugs; parasite and predator populations will be made more efficient by application of chemicals secreted by beneficial and pest insects which control egg-laying and host search behavior and by spraying artificial foods on crops to hold predators/parasites in a given location; new weed-feeding insects will be introduced and established for control of Canada plumeless milk and yellow starthistles, mesquite, leafy spurge, knapweed and others; weed pathogens will be introduced and developed for control of curly dock, hemp sesbania, spiney cocklebur and others; new strains of bacteria will be discovered and developed for direct infection of plant and animal feeding insects and for production of bacterial toxins (in addition to the delta endotoxin and beta exotoxin of Bacillus thuringiensis) for control of such difficult species as the corn earworm/tobacco budworm complex; new insect viruses, fungi, fungal toxins and protozoa will be discovered and developed for control of a wide spectrum of insects affecting plants, livestock and man; plant pathogens will be identified and established to control such plant diseases as crown gall of fruits, common root rots of wheat, chestnut blight and many others.

The technological advances for the next 10 years in insect taxonomy are difficult to visualize because it is difficult to predict which species need to be classified and identified. A thorough and accurate classification of all insects and mites is impossible. Probably no more than 50% of the total insects and mites of the world can be described and classified over the next 100 years with present levels of support. On the basis of past accomplishments ARS taxonomists would expect to make over 801,000 identifications of insects and mites during the next 10 years in support of action agencies and other Federal-State research programs.

C Consequences of Combined Visualized Technology.

1 Increase agricultural production and quality where other types of pest control are ineffective, do not exist, or are not feasible due to low acre value of crop.

2 Lower costs of agricultural production.

3 Reduce environmental pollution and hazards to man and animals due to pesticide residues in soil, water, and air.

4 Decrease the amount of natural resources and energy used in the manufacture and application of pesticides.

5 Utilize waste products (nitrogenous and carbohydrate) for production of biological pesticides.

6 Create new industries concerned with production of biological agents and their dissemination, artificial foods and behavioral chemicals.

7 Decrease the cost of biological and taxonomic research by utilization of computer modeling and more efficient means of selecting natural enemies for testing.

8 Decrease the probability of resistance to chemicals in pest species.

9 Allow removal of selected pests without disturbing the effectiveness of existing beneficial organisms.

10 Increase store of scientific information for use in the development of pest control technologies 20-30 years in the future.

11 Decrease income of chemical pesticide industry.

12 Possible replacement of one pest with another as in the case of where some weed species are eliminated.

13 Possible pollution of streams from erosion due to total elimination of some weed pests.

D Total Potential Benefits. Considering the cumulative benefits due to reduced treatment costs and damage, it has been estimated that biological control importation programs will easily return $30 in benefits for every $1 spent on a program for the introduction of natural enemies. Even assuming a projected 25% success rate (for complete or substantial control) over the next decade, which can be expected without an expansion of current efforts, instead of the optimum 40% rate, an estimated $18.75 return for every $1 invested in the ARS natural enemy importation program can be expected, an extremely favorable ratio (this compares well with the estimated $5 benefits for each $1 spent in development of new insecticides). Actually, benefits would be even greater considering the unmeasurable benefits accruing from only partially successful programs (DeBach, P., Biological Control by Natural Enemies, P. 192, Cambridge Univ. Press, 1974).

The effective utilization of native parasites and predators could save $200,000 for every million dollars currently spent on insecticides. Likewise, the amount of energy expended for the current level of insecticide

production should be decreased by 20% in ten years. Assuming that there will be no counterproductive results from increasing indigenous beneficial insect usage, environmental pollution should be reduced 20% over the next decade. The research effort required to determine the feasibility of individual augmentation and conservation programs should be reduced 25% over the next 10 years. This will be a net result of efforts expended to gather input data for computer simulations of the Visualized Technology.

Analysis of previous control efforts with weed-feeding insects suggests that any particular project will have an 82% probability of attaining partial, substantial, or complete success. Within this broad category there would be a 70% chance of partial success and 30% chance of substantial success. These figures can be extrapolated to the musk thistle project now in progress. This weed is estimated to cover 2 million acres. The current chemical control costs $6/acre. Thus, a 30% reduction in acreage (600,000 acres) could produce a savings of $3 million/year in control costs alone.

Those diseases that infect insects and those that produce harmless toxins (such as Bacillus thuringiensis) offer the benefit of safety. They will not pollute the environment since they occur there naturally; and they will not harm beneficial insects. Because these microbial insecticides have the potential to replace large quantities of chemicals, it can be considered a benefit each time one replaces a chemical. Table 1 shows the potential effects of insect diseases being researched currently. All these goals are in sight given adequate staffing and funding, and as the table shows, it is possible to visualize 36 million pounds of chemical insecticides being replaced by microbials with the market for the microbials approaching $330 million by 1986.

Estimated losses and potential benefits from the use of plant diseases against northern jointvetch, a weed which infests the Arkansas, Mississippi, Louisiana area, and prickly sida which is an increasing problem in Alabama, Arkansas, Georgia, Louisiana, Mississippi, North Carolina, South Carolina and Tennessee, are shown in Table 2. These are but 2 examples in a rapidly developing field of research.

The magnitude of benefits from control of plant diseases with biological agents are difficult to estimate because this research field is so new. However, the following examples appear to be realistic:

1 Control of Verticillium wilt of potatoes could increase potato yields in the irrigated west by 50 cwt per acre while eliminating the current practice of soil fumigation which costs $100 per acre.

2 Control of Fusarium wilts of peas and tomatoes, the two main vegetable crops affected in the U.S., could increase yields by 25-50% in fields presently affected while decreasing current massive programs in the public and private sectors on breeding for resistance, and allow return of certain preferred varieties.

3 Development of soils antagonistic to cortical rotting fungi (soils microbiologically suppressive to *Rhizoctonia*, *Fusarium*, *Pythium*, or *Phytophthora*) would benefit the avocado, cotton, apple, pear, strawberry, alfalfa, wheat, potato, tobacco, pea, bean, soybean, corn, and other industries since annual losses in each of these crops by one or more of the above pathogens is a conservative 5%.

4 Control of the chestnut blight fungus by hypovirulent relatives of the pathogen could restore stands of this prized hardwood tree, now nearly extinct in the U.S. Similarly, control of the Dutch elm disease by an antagonist injected into the trunk could save this magnificent tree species from doom in the midwest.

TABLE 1. POSSIBLE ANNUAL RETAIL VALUE OF CROP PROTECTION BY MICROBIAL AGENTS BY 1986 1/

Crop	Annual Acreage Grown X1000	Acreage Treated with Insecticide X1000	Pounds Insecticide Used X1000	Possible Pounds Replaced by Microbial Agents X1000	Dollar Value 2/ X1000
Vegetables	3,333	1,866	8,494	3,000	27,000
Corn	74,055	25,919	27,315	5,000	45,000
Cotton 3/	12,355	7,540	73,365	25,000	225,000
Tobacco	839	646	4,143	2,000	18,000
Potatoes 4/	1,432	1,102	2,889	1,400	13,000
Rangeland	270,000 5/	735	333	6/	2,000 6/
			TOTAL:	36,400	330,000

1/ Estimates based on the production of crops and use of insecticides in 1971; Agric. Econ. Rep. 252 (1974), 268 (1975).

2/ Dollar value computed by assuming the retail value of a microbial insecticide equivalent to 1 pound of a chemical insecticide is $9.00. This is reasonable by current costs.

3/ Does not include treatments for insects other than *Heliothis* spp.; includes viruses.

4/ Treatment for green peach aphid only; *Entomophthora thaxteriana*.

5/ Estimated total pastureland in northern plains and mountain States.

6/ For control of grasshoppers only; assuming less than 1/10 of land infested with grasshoppers is now treated, and that successful development of *Nosema locustae* would permit treating all land infested, the dollar value represents estimated annual benefit rather than the cost of the chemicals replaced.

TABLE 2. LOSSES AND BENEFITS ESTIMATED FOR CONTROL OF 2 WEEDS THROUGH THE USE OF NATIVE PLANT DISEASES

Weed	Crop	Acres infested[1/] (thousands)	Losses[2/] %	Losses[2/] $ Million	Benefits from use of bioagents[3/] %	Benefits from use of bioagents[3/] $ Million
Northern jointvetch	Rice	165	6	4.2		
	Soybeans	330	3	1.5		
			TOTAL	5.7	50	2.8
Prickly sida	Cotton	233	5	2.6		
	Soybeans	405	5	2.5		
			TOTAL	5.1	5	.3

1/ Data obtained from extent and cost of weed control with herbicides and an evaluation of important weeds, 1968. ARS-H-1, 1972; Research Report of the Southern Weed Science Soc. 1974.

2/ Percent loss values based on research reports. Dollar losses calculated from acres infested, average yield of crop, average price of crop, and assigned percent loss values.

3/ Percent benefit values based on research for northern jointvetch and prickly sida.

E Total Research Effort.

Technological Objective No. 1 - Discovery, evaluation of biological control agents in foreign countries and introduction for control of insects, weeds, plant pathogens and other pests.

	Year	Current Support SY's	Current Support Gross Dollars	Expanded Effort[1/] SY's (ARS Only)
ARS	FY76	20.8	1,563,275	48.5
SAES	FY76			--
Other	FY76			--
Total				48.5

1/ Includes base and additional SY

The major factors limiting research progress are lack of staff and funds for discovery of beneficial insects, pathogens, and antagonists in foreign countries, then importation and utilization in the U.S. Permanent facilities should be established in the Middle East, Far East, and South America to provide biological control agents for use in the U.S.

Technological Objective No. 2 - Increase conservation of introduced and native biological control agents for control of insect, weeds, plant pathogens and other pests.

	Year	Current Support SY's	Gross Dollars	Expanded Effort 1/ SY's (ARS Only)
ARS	FY76	17	1,976,942	39.0
SAES				--
Other				--
Total				39.0

1/ Includes base and additional SY

The major factors limiting research project are lack of staff and funding (1) to provide team approaches in beneficial insect rearing for augmentation, (2) to exploit opportunities in the use of behavioral chemicals for manipulating parasites and predators in the field, (3) to explore new types of microbial insecticides, (4) to capitalize on the promising research advances in control of weeds with plant diseases, and (5) to pioneer in the field of control of plant diseases with biological agents.

Technological Objective No. 3 - Insect and mite identification.

	Year	Current Support SY's	Gross Dollars	Expanded Effort 1/ SY's (ARS Only)
ARS	FY76	28.8	845,000	40
SAES	FY75	7.6	365,123	--
Other	FY76	10.3	427,339	--
Total		46.7	1,637,462	40

1/ Includes base and additional SY

Additional staffing and funding would provide more expertise in large taxonomic groups in order to keep up with the increasing number of identifications requested by Federal and Stage agencies, and to provide subprofessional assistance so as to make the professional staff more effective. Additional space is needed for staff and for insect collections which grow in size continually as would be expected of an effective identification program.

NOTE: The expanded support level reflected in this National Research Program represents staff views as to the additional level of staffing that can be effectively used in meeting the long-term visualized objectives for this program. These do not reflect commitments on the part of the Agency.

III TECHNOLOGICAL OBJECTIVES

III.1 New and improved technology for discovery and evaluation of biological control agents in foreign countries, and introduction for control of insects, weeds, plant pathogens, and other pests.

A Current Technology

1 Parasites and predators. There are about 10,000 pest insect and mite species in the U.S. that reduce the potential agricultural production by at least 30%. In addition, many transmit diseases of plants, animals and man. Of these, 751 have been accidentally introduced to the U.S., including 249 of the 700 species classified as important agricultural, forestry or horticultural pests. Thus, about 35% of our important pests are of foreign origin. Moreover, despite our quarantine vigilance, new alien pests of major importance are found in the U.S. at the rate of one every 3 years.

Many of these accidentally introduced species are more important as pests in the U.S. than in their native homelands because they were introduced without their own complexes of natural enemies that serve to keep them in check in their original homeland. Experience has shown that most insects and other arthropods are hosts or prey of at least 3 more or less specific entomophagous insects, and the number of such natural enemy species, including those of less specificity, can reach 40 or 50 per pest species. The pest potential of species introduced to new environments without these natural enemies to control their population expansion is obviously great.

The importation of natural enemies represents an inexpensive means of increasing production of food and fiber, without hazard to the environment, and with low energy expenditures. When successfully established, introduced natural enemies are self-perpetuating pest control agents, causing no environmental pollution. If effective, they actually reduce pollution by lessening the need for insecticides; and the use of energy needed to produce and apply pesticides is also reduced, or in some cases, eliminated.

There are an estimated 200,000 arthropod species throughout the world classified as beneficial. There are estimated to be over 5,000 entomophagous nematodes. This represents a tremendous reservoir of material of potential benefit to American forestry, horticulture, and agriculture. At the current level of effort, about 1.25 beneficial species have been introduced and established in the U.S. per year since 1890 against the estimated 10,000 pest species now in the U.S. (Only one nematode has been imported and released, but it is not known to be established). At this rate, it would take centuries to introduce all species of potential benefit to the U.S. When it is also considered that new pests accidentally enter this country at a rate of about 1 every 3 years, the current rate of purposeful introduction of beneficial species appears particularly slow. More attention to the potential of beneficial nematodes is also needed.

In the past 90 years, USDA and SAES entomologists have been conducting explorations in foreign countries to seek out and study natural enemies for introduction into the U.S. to combat their host species which have entered and become pests in the U.S. A recent compilation lists 155 arthropod parasites and predators established in the U.S. as a result, though the number of species actually imported and released is over 500. Over 80 arthropod pests have been targets of these introductions which have resulted in the complete or substantial control of at least 15 pest species, solely by introduced natural enemies; others have given significant control when combined with other methods such as host plant resistance. On the surface this would appear to be a 20% success ratio. However, many other pests have been partially controlled, i.e., chemical control is commonly necessary, though reduced. Of many reasons for failures, a most significant one is lack of sufficient funding and effort devoted to the importation program. Organizational difficulties in the search, shipment, distribution, and utilization of natural enemies is another important factor.

Some past examples of successful biological control programs include the well known successful control of the cottony-cushion scale by the introduction of the vedalia beetle from Australia in 1888, which saved the then infant California citrus industry at a cost of less than $5,000 and has been saving millions of dollars annually since that time. Other past examples include control of the citrus blackfly in Mexico, the brown-tail moth in New England, the Florida red scale in Florida and California, the purple scale in Florida, the larch casebearer in the northeastern U.S., the oriental moth in New England, Rhodesgrass scale in Texas, the satin moth in New England, and the spotted alfalfa aphid in the southern U.S. (For other examples see Sailer, R. I., "A Look at USDA's Biological Control of Insect Pests: 1888 to Present," USDA, CSRS, Agricultural Science Review, Vol. 10, no. 4, pp. 15-27, 1972).

A 1969 tabulation of biological control attempts on a worldwide basis shows that of 223 attempts, 90 cases (40.3%) have resulted in complete or substantial control, 30 cases (13.5%) have resulted in partial control, and 103 (46.2%) gave no results. The 1969 figures indicate that the chances of some significant degree of success against any given pest species by importation of natural enemies are about 54%; substantial or complete control can be expected in 4 pest species out of 10, that is, insecticide treatments can be eliminated or substantially reduced in about 40% of the cases.

Furthermore, the cost-benefit ratio of natural enemy importation programs is extremely favorable. Recent estimates indicate a $30 return for each dollar invested in importation and colonization of natural enemies, as compared with $5 for each dollar spent on insecticide research (DeBach, P., Biological Control with Natural Enemies, Cambridge Univ. Press, p. 193, 1974).

A recent example of successful progress in the utilization of imported natural enemies in the past decade may be cited as far as cost-benefits are concerned. As a result of an importation program initiated in 1957, 5 exotic parasites have been established that attack the alfalfa weevil, the nation's number one pest of the important forage crop, alfalfa. These

parasites were first established in New Jersey where they now exhibit their greatest effectiveness. Surveys have shown a dramatic decrease in alfalfa weevil populations in Jew Jersey and a corresponding decrease in use of insecticides to control the pest -- 94% of New Jersey alfalfa growers used insecticides in 1966 while only 8% did so by 1970. By 1975, there was an estimated 80% reduction in the acreage sprayed for the weevil in New Jersey. Savings to farmers in New Jersey and 12 other States where the parasites are now established have been calculated at over $7,000,000 in 1975 alone, considering only per acre costs of insecticides not applied. Such annual savings are, of course, cumulative (the corresponding 1970 figure was $3,000,000) and increase as the parasites are dispersed further. The cost of the alfalfa weevil parasite importation program, now in its 17th year, is estimated to be about $825,000. This has been repaid nearly 10 times by savings resulting in 1975 alone. In time, these benefits will easily surpass the 30:1 estimates of cost/benefit ratio of which biocontrol importation programs are capable.

The cereal leaf beetle, a serious threat to the over 40 million acres of American wheat, oats, and other small grains, was first found in this country in 1962. Explorations began in 1963 in Europe for its natural enemies. As a result, 4 species of parasites are now established on this pest. High rates of parasitism are being observed, but it is too early to quantify the effects. The parasites are dispersing and are being distributed by APHIS personnel and established in several other more Eastern States where the pest has now spread.

Another example of large potential benefits from importation programs is that of natural enemies of the Mexican bean beetle. This pest is a serious threat to the soybean crops of many Eastern States. In the 1950's, an ARS entomologist discovered a parasite of a species related to the bean beetle in India. This was introduced in 1966. It quickly demonstrated its effectiveness against the pest, but it was also found to be unable to overwinter in this country. Therefore, studies were conducted on the potential utilization of this parasite in a pest management program whereby the parasite could be reintroduced early in the season each year. These studies, conducted in Maryland by SAES personnel, proved immensely successful. Parasitism reached 80-90%, and need for insecticides in some Maryland counties dropped sharply in 1974--in one county, only 13% of soybean acreage was sprayed as opposed to 50% in each of the two previous years. The parasite is now also being studied for pest management utilization by entomologists in New Jersey, South Carolina, Florida, Guam, and Mexico.

During the past 10 years, at least 200 species (identification difficulties prevent a more exact figure) of exotic natural enemies have been received in the quarantine facilities of the ARS Beneficial Insects Research Laboratory now at Newark, Delaware, the primary USDA center for receipt and quarantine clearance of biological control material from ARS or other facilities overseas. A total of 181 exotic or newly established species were released from quarantine for field release or shipment to cooperators for study, propagation and release (field release did not necessarily take place in all cases). A total of 39 pest species

were the targets of these importations. The number of establishments during this period is difficult to determine with certainty, but is estimated to be 10 beneficial species against 9 pests. An eleventh imported beneficial species is being effectively utilized in a pest management program against a tenth pest (the Mexican bean beetle). In addition, 8 beneficial species that had previously established only in small areas were distributed and established over much wider areas in several other States against two insect pests (alfalfa weevil and cereal leaf beetle) by ARS, APHIS, and State personnel.

Some recent programs for which increased efforts are planned include importation programs against lygus bugs, gypsy moth, greenbug, and alfalfa blotch leafminer.

Lygus bugs. No recent figures exist indicating the damage and control costs attributable to these pests of cotton, forage, and many other crops, in the whole of the U.S. However, the total yield loss and control costs for California alone in 1974 was estimated at nearly $57 million (Calif. Dept. Food and Agric., E82-14, Sacramento, 1975. 14 p.). In 1965, annual losses in cotton in the entire U.S. due to lygus bugs and other sucking insects were estimated to be over $85 million; similar damage to alfalfa seed production due to lygus bugs alone was estimated to be nearly $13 million. Current national damage caused by lygus bugs in cotton, forage seed, and crops should easily exceed $150 million a year.

In the past few years, releases of several European parasites of lygus bugs have been made, but there is no indication of establishments. There has been insufficient effort in foreign exploration for lygus bug natural enemies, and current plans provide for expanded explorations in Europe and Asia for a period of 3-4 years.

Gypsy moth. This introduced forest pest defoliated 1.7 million acres of woodland in the northeastern U.S. in 1973, and over 750,000 acres in 1974. Defoliation figures fluctuate depending upon the cyclic nature of population expansions of the gypsy moth. It is difficult to place accurate cost figures on the damage caused by this pest, because some damage occurs in woodlands in which the end effect may not be attained until the trees die as much as 7 years after the initial defoliation; in residential and recreational situations losses also include aesthetic and nuisance factors which have high public visibility. If a nominal loss figure of $20/acre were placed on the 750,000 acres defoliated in 1974 the total would be $15 million.

Early introduction programs (1905-1933) resulted in the establishment of 12 parasites and predators. It is generally considered that these have had considerable impact on gypsy moth populations, but their real impact has never been measured quantitatively. This is partially due to the lack of complete knowledge of the population dynamics of the gypsy moth itself. As a result of the recent expansion of the range of the gypsy moth following cessation of DDT treatments in the early 1960's, a new exploration and importation program was begun in 1972. To date, no new establishments have resulted. Concentration has been on foreign

exploration; more emphasis is now needed on domestic studies to effect establishment and evaluate new parasites. The overseas program is scheduled to continue until 1978.

Greenbug. In 1976, crop losses and control costs in small grains due to this aphid in Oklahoma were estimated at $72 million by the Oklahoma State Department of Agriculture; Kansas costs were $28 million; South Dakota and Nebraska losses were $5 million. The 1975 costs for control of a biotype of the aphid discovered in 1968, which attacks sorghum, were estimated at $25 million for Kansas, Nebraska, Oklahoma, South Dakota and Texas. The latter State accounted for 12-14 million of the total.

Some natural enemies were introduced following discovery of the sorghum biotype. However, there were considerable biosystematic problems in connection with some of these. Additional foreign explorations and domestic biosystematic studies are currently underway and overseas studies will continue for 2-3 years.

Alfalfa blotch leafminer. This pest was first found to have been accidentally introduced in Massachusetts, in 1969, and has since spread throughout much of the northeastern U.S. and into Canada. The pest was estimated to cause about a 10% crop loss in Massachusetts in 1969-1970, or a loss of about $9/acre. High infestations can cause even higher losses. It has been estimated that 1 miner per alfalfa leaf can cause a 16% loss in protein of that leaf. Thus, 25% infestation in a field of alfalfa, a common level of infestation, causes 4% loss of protein in the harvested hay. Infestations of 58% or more are also recorded, and some alfalfa fields have been reported to be completely stripped of leaves.

Exploration for parasites began in Europe in 1970-1971, and the first parasites were released in the U.S. in 1975. The foreign studies will continue for 2-3 years, and domestic work will continue for at least 4-5 years.

One bottleneck in successful establishment of introduced parasites and predators is the fact that in most cases introduced species leave the control of qualified ARS biocontrol entomologists once they are cleared through quarantine facilities. Most of the past successful programs have been those in which ARS biocontrol workers intimately associated with the foreign and quarantine phases of the program have also been those involved in the release and establishment phases, e.g., in the case of the alfalfa weevil program. There is a need for more qualified biocontrol workers in each region working on commodities or groups of commodities to work with imported natural enemies, and to work as part of a cohesive team from the discovery to the establishment phase of the importation program.

To increase the numbers of target pests and numbers of beneficial species introduced, released, and established without a corresponding increase in amount of ARS research personnel, it will be necessary to increase effective cooperative activities with other federal agencies, SAES, universities, and state departments of agriculture, etc., from the current estimated 35% to about 50% of all ARS exploration, quarantine, and distribution efforts.

Another bottleneck is in the need for recolonization of established parasites. Current ARS research personnel are heavily involved in the dispersal or recolonization of alfalfa weevil parasites that have become established and have demonstrated their effectiveness. This work is done at the expense of new release and establishment studies. Recolonization and dispersal of established parasites of proven effectiveness throughout the entire range of the target pest is more logically a regulatory function than a research function, i.e., it would be helpful to have more involvement of APHIS personnel in this phase of operations. The current, highly successful APHIS program for the recolonization of cereal leaf beetle parasites is an excellent example of ARS-APHIS cooperation in biocontrol importation programs. Evaluation of the established parasites should be a function of ARS in close collaboration with APHIS, as part of the team approach to the importation and distribution program.

Increases in numbers of target pests and beneficial species imported and released cannot as such guarantee an increase in the rate of successful programs. These increases and the increase in number of cooperators should increase the likelihood of successful control. However, with no increase in number of ARS biological control personnel involved in importation programs, the likelihood of successful programs can be expected to increase from 20% to only 25%.

Better coordination of the importation programs would result and the likelihood of success could be increased nearly to the 40% level, with the addition of strategically placed ARS biocontrol entomologists in the U.S., who would be more intimately involved with all 3 phases of the importation program: foreign exploration, quarantine clearance and study, and release and establishment.

A third serious roadblock in the current ARS biocontrol importation program is the insufficient current level of effort and support for overseas activities. There are currently too few entomologists and support technicians overseas to service all requests for overseas research and collections of natural enemies. This is particularly critical if domestic biocontrol activities are to be augmented by elimination of the two bottlenecks discussed above.

2 Insect pathogens. Research and development for the utilization of microbial insecticides is a relatively new field. Consequently, exploration for entomopathogens in foreign areas has been neglected, generally because of the preoccupation of insect pathologists with research on native insect pathogens and because of the lack of pathology expertise and facilities in ARS and other biological control laboratories outside the U.S. Although nuclear polyhedrosis viruses have been discovered and introduced for control of the pine sawfly, the gypsy moth, corn earworm, tobacco budworm, *Bacillus thuringiensis* for control of lepidopterous pests, and *B. popilliae* for control of the Japanese beetle, foreign sources of entomopathogens have not been exploited to any degree comparable with that of entomophagous insects. There is reason to believe that successes similar to those achieved with exotic parasites and predators could also be achieved by the introduction of insect disease producing agents from foreign countries. However, systematic search for entomopathogens in foreign areas will not be made until foreign ARS laboratories are provided with diagnostic expertise and facilities.

3 Weed biotic control agents except pathogens. All plants have natural enemies which, along with other environmental factors, regulate their abundance and distribution. It is only when this combination of factors fails to hold a plant in check below the level of economic importance that the plant becomes a weed and control measures are sought. Biological control strives to regulate the abundance of weedy plants by increasing the stress on the plants with their own natural enemies.

The steps currently followed in developing a biological control program are: (1) select target weeds for biological control; (2) survey weed problem for natural enemies already present; (3) map range of weed in problem area and determine occurrence of plant in other areas of the world; (4) compile a listing of recorded natural enemies; and (5) survey the weed in areas to which it is considered native or wherever there is a likelihood of finding new natural enemies.

At this point the researcher must assess the potential of natural enemies for solving the weed problem and decide on the approaches he will follow: (1) to search out new natural enemies (Technological Objective I), or (2) manipulate those natural enemies already at hand (see Technological Objective II). Of the two, the introduction approach has been the most fruitful to date. In this case the researcher will: (1) collect and study natural enemies throughout the plant's range (that is, conduct host specificity tests and biological and behavioral studies), (2) summarize the information on all potentially useful weed control organisms in order to ascertain safety of their use in new areas, (3) clear the introduction of the new organisms with importation officials (e.g., Working Group on the Biological Control of Weeds, APHIS, various state quarantine officials), (4) introduce the organisms, note establishment, make redistribution and (5) measure impact on the weed.

Almost any plant feeding organism may have potential for controlling weeds. In some instances, geese and ducks have been utilized to weed row crops; herbivorous fish, the manatee and snails have been studied as potential control agents in aquatic habitats; plant pathogens have been introduced into new areas and/or manipulated to increase weed kill; and weed-feeding insects have been imported from the native areas of weedy plants to areas where the weeds are a problem. Thus the search for natural enemies should encompass all organisms associated with the target weed.

The type of organisms to be used for biological control is determined for the most part by the weed species involved and the particular problem at hand. If control of a single weed species is desired, the host specificity of the controlling agent is important to protect surrounding plants from damage. If total plant removal is the desired end, the more polyphagous organisms can be used (goats, geese, etc.). In most instances biological control has been used to remove single weed species from the plant community in areas of relatively low disturbances (range, aquatic, pasture, etc.). Although some of our greatest weed losses occur in crop areas, the multiplicity of weed species involved at any one site, the high degree of disturbance (cultivation, harvest, etc.), and

the general amelioration of natural environmental stresses acting against the plant, through modern cultural practices (irrigation, fertilization, etc.), make crop weeds potentially more difficult to control with natural agents. For biological control to be effective against crop weeds, some form of augmentation or manipulation (see Technological Objective ID) is needed to reduce the time from introduction or application of the biotic agent until control is achieved.

This section of the NRP will be concerned chiefly with the biological control of weeds in areas of low disturbance primarily with weed-feeding insects. The latter have proved of great value in weed control and hold considerable potential for future use, especially against introduced weed species (approximately one-half of the major weeds in the U.S. are introduced plants). The potential and use of other types of organisms will be discussed in NRP 20280 (Aquatic Weeds--fish, competing plants, etc.). Many of the steps and principles of biological weed control with insects discussed here are applicable to the use of other natural enemies against weeds.

Generally, it takes anywhere from 2-4 years from the time of discovery to the clearance of an exotic insect for introduction to the United States, although this time may run longer (e.g., insects on alligatorweed, Agasicles beetle 1959-1964; Vogtia 1959-1971; insect on Russian thistle, Coleophora 1965-1973). This extended time is due to administrative and logistical difficulties, the complexity of the insect's life cycle and host selection behavior, its taxonomic position with respect to economic insect pests and the taxonomic relationship of the weedy plant to crop plants, and rarely due to technological difficulties in the testing itself. Cost estimates for clearing an insect may run from 1/4-1 million dollars, depending on the amount of testing required and the number of species that can be studied concurrently.

Assurance of host specificity and safety of introduction are the prime concern in dealing with exotic plant-feeding insects. Until there is relative certainty that the weed-feeding insects are host specific, studies are carried out in the native range of the insects--although limited handling may be permitted in a domestic quarantine facility (e.g., to rear and observe insects when native area is inaccessible, or does not permit proper study conditions). The foreign work is carried out by cooperators or by U.S. personnel stationed in, or traveling through the area. Final testing with plants indigenous to the U.S. and handling of the candidate insects is done in a domestic quarantine laboratory.

Host specificity testing involves exposing the insects to various test plants caged singly or in combination with other plants and/or the preferred host plant. The amount of feeding is recorded, adults are dissected to observe oogenesis, oviposition attempts are noted, and the development of the immature stages followed. Observations on the host selection behavior are analyzed and the seemingly important morphological and chemical characteristics of the host noted and their presence or absence in other plant species ascertained. Based on these observations, a decision is made as to the safety of introduction.

Host specificity testing is time consuming at best and is one of the factors governing the number of exotic insects available for weed control purposes in the U.S. Often the basis of host selection is poorly understood, if at all. Although increased understanding of the insect-plant relationship would place this work on a more scientifically sound basis, it probably would not reduce the time required for clearance. However, it may serve to increase the acceptance of species otherwise rejected during the testing process due to abnormal behavior resulting from one or more experimental artifacts.

In view of the time spent clearing insects for introduction, it would be useful if we could predict which species have the greatest control potential. Successful control depends on a number of factors (e.g., establishment, buildup, type of damage, timing of attack, other environmental stresses on the plant, etc.) that make the predictions of success uncertain at best. A method of evaluating the control potential of an insect by rating its various behavioral characteristics, its range of distribution, etc., has been proposed, but is as yet unproved. One of the most important factors predetermining successful biological control is the amount of environmental stress exerted on the plant by the habitat (e.g., water supply, nutrients, temperature extremes, periodic disturbance). When the insect feeding damage complements these existing stresses in sufficient amount, control is usually assured. Thus, two things are required to improve the predictability of success: (1) detailed information on the weed habitat and the existing stresses imposed by that habitat and (2) the nature of the insect's attack on the plant (i.e., tissues destroyed, importance of these tissues to normal development and growth of the plant and plant populations, etc.). Close cooperative studies between entomologists, plant physiologists and agronomists will be needed to resolve these two points. The plant scientist should be able to provide clear-cut information on the distribution of the weed, precise identification of the species, and suggested areas where it quite likely originated, biological information on the plant life cycle, productivity in various parts of its range and those factors which seemingly limit plant growth and spread (See NRP 20280). The entomologist should define the insect life cycle, reproductive potential under various conditions, factors limiting growth, plant tissues destroyed, and timing of attack. The plant physiologist will relate insect attack to the overall physiological condition of the plant and indicate to what extent the attack is influencing plant development.

Once clearance for introduction has been granted, releases of exotic insects are made in several habitats selected on the basis of climatic and physiognomic characteristics and lack of disturbance by man. Subsequent releases may be made at the same or similar sites, depending on ease of establishment. Of 30 spp. of insects released in the U.S. for weed control, 19 have established, 4 have failed to establish, and 7 are uncertain as to establishment (See Table 1). The USDA originated or participated in specificity test studies on 14 of the 30 spp. insects. The remainder are considered transfer projects, that is the studies were initiated by other research organizations (e.g., Canada Department of Agriculture, CSIRO, the University of California, etc.) and only partial testing and minimal handling was performed by the USDA.

Table 1. Insects Introduced to the Continental U.S. for Weed Control Purposes

	Weed Species	Insect Species	Establishment
1.	*Alternanthera philoxeroides* (alligatorweed)	*Agasicles hygrophila*	+
		Amynothrips andersoni	+
		Vogtia malloi	+
2.	*Carduus nutans* (musk thistle)	*Rhinocyllus conicus*	+
3.	*C. acanthoides* (plumeless thistle)	do	+
		Ceutorhynchidius horridus	(1975)?
4.	*C. pycnocephalus* (Italian thistle)	*Rhinocyllus conicus*	+
5.	*Centaurea diffusa* (diffuse knapweed)	*Urophora affinis*	+
6.	*C. solstitialis* (yellow starthistle)	*Urophora siruna-seva*	-
7.	*Chondrilla juncea* (skeletonweed)	*Cystiphora schmidti*	(1975)
8.	*Cirsium arvense* (Canada thistle)	*Altica carduorum*	-
		Ceutorhynchus litura	?
9.	*Cytisus scoparius* (Scotch broom)	*Apion fuscirostre*	+
		Leucoptera spartifoliella	+
10.	*Eichhornia crassipes* (waterhyacinth)	*Neochetina eichorniae*	+
		N. bruchi	(1975)
11.	*Euphorbia esula* (leafy spurge)	*Hyles euphorbiae*	?
12.	*Halogeton glomeratus* (halogeton)	*Coleophora parthenica*	(1975)
13.	*Hypericum perforatum* (St. Johnswort)	*Agrillus hyperici*	+
		Chrysolina hyperici	+
		C. quadrigemina	+
		C. varians	?
		Zeuxidiplosis giardi	+
14.	*Linaria dalmatica* (Dalmatian toadflax)	*Calophasia lunula*	-
15.	*Salsola iberica* (Russian thistle)	*Coleophora parthenica*	+

16. Salvia aethiopis (Mediterranean sage)	Phrydiuchus spilmani	-
	P. tau	+
17. Senecio jacobaea (tansy ragwort)	Hylemya seneciella	+
	Longitarsus jacobaeae	+
	Tyria jacobaeae	+
18. Silybum marianum (milk thistle)	Rhinocyllus conicus	+
19. Tribulus terrestris (puncturevine)	Microlarinus lareynii	+
	M. lypriformis	+
20. Ulex europeaus (gorse)	Apion ulicis	+
	Total 30 insect species	

Projects of greatest note include:

(1) St. Johnswort control primarily by the European beetle, Chrysolina quadrigemina. This insect has given an estimated 99% control of this weed in California and has reduced the abundance in other northwestern States to where it is a minor pest only periodically.

(2) Alligatorweed control primarily by the South American beetle, Agasicles hygrophila, and the moth, Vogtia malloi. The final outcome of this project is yet to be determined, although this weed has already lost much of its stature as an important aquatic pest.

(3) Tansy ragwort control by a European leaf and flower-feeding moth, Tyria jacobaeae, and rosette-feeding flea beetle, Longitarsus jacobaeae. Tyria effectively reduced plant size and seed production in some areas. The introduction of the flea beetle has placed added stress on the plant and is now reducing the actual plant numbers. There is a major effort underway to spread Tyria in Oregon and Washington.

(4) Puncturevine control with the seed and stem weevils (Microlarinus lareynii and M. lypriformis) in California. These weevils have reduced plant abundance by 50% or more in some areas and have reduced or eliminated the need for roadside spraying. The weevils are now well established throughout the southwest and up to the Kansas-Nebraska border. Other natural enemies are being sought.

Biological control is operational on all of these projects and is a consideration in the development of a weed management program wherever these weeds might be involved.

Since the mid 1950's, the USDA has invested approximately 127 SY's in the biological control of weeds with insects. An estimated 50 SY's have been in overseas work. Work by various State institutions and universities on the biological control of weeds has been effective but limited. The

State of Hawaii, the University of California, and Virginia Polytechnic Institute have all participated in the testing and clearance of candidate species. Hawaii usually conducts its own program independently. Programs at the other two institutions named are carried out in cooperation, and partially supported by the USDA. The USDA is by and large the principal U.S. research organization in the field due to the resources needed to carry on an active foreign program. The technology of weed control with insects does not lend itself to commercial development. The rate at which the insects are introduced and spread to other areas depends on Federal, State, and private funding. Once released in an area they either provide adequate control or not. An analysis of control failure is required, but seldom performed.

To conclude briefly, although a proved biological control of weeds technology has evolved over the past several decades and which has afforded substantial progress, several problems do exist, namely:

1. The selection of target weeds and assignment of study priorities. Over one-half of the major weeds in the U.S. are introduced species, however, many of these are unsuited for biological control due to conflicting interests, close relationship to economic plants, etc. Criteria and a mechanism are needed for judging the importance of a weed (i.e., area infested and potential for spread, damage caused, conflict of interests over control, etc.), and the possibility of biological control. To date, the selection of target weeds has been pretty much up to the biological control worker with only minimal input from the weed scientists. Since the foreign work progresses best if the project objectives and target species are well defined, an improved system of selecting weed projects is needed.

2. Shortage of biological control agents: The success of a project is often in direct proportion to the number of natural enemies available for introduction. To increase the availability of biotic agents we must: (a) increase the survey for natural enemies and (b) improve our capability to select out those agents that will be safe and effective species. The number of insects available for introduction reflects partly on the ability and number of persons conducting the overseas program, their resources (i.e., equipment, facilities, etc.), and their flexibility to travel to where the natural enemies occur. These are essentially problems of a logistical or administrative nature and can be solved through improved planning and the development of realistic administrative procedures.

However, some insects are rejected because of feeding on laboratory test plants, although, they have never been recorded from these same plants in the field. Thus, studies are also needed into the host selection behavior of these insects and an improved method of determining the safety of their use.

3. Poor followup of introduced weed-feeding insects: The failure to fully document the control or lack of control increases the difficulty of planning and justifying future research projects. Detailed followup studies should also add to our understanding of the role of insects in relation to plant abundance.

4 Weed pathogens. Many of the steps required for developing pathogens as weed bioagents are similar to those discussed for weed controlling insects. These steps include surveys for and identification of weed pathogens in lands native to the weed; determining areas where the plant exists as a weed; collecting and researching the weed pathogens including research on host specificity, epidemiology, and effects on the weed host; determining safety of foreign pathogens; obtaining permission to introduce the weed pathogens into the U.S. from responsible importation agencies under quarantine authority for study in containment. Eventually, the objective is to release for use the biocontrol agent, but presently releases of foreign weed pathogens into crop environments of the U.S. are restricted. Research on the pathogen can be conducted in the country native to the weed and the pathogen. Government and private agencies have expended very little effort in conducting surveys and research with weed pathogens. Excellent opportunities exist for developing pathogens to control weeds as evidenced by the limited research conducted up to now.

The rust fungus (Puccinia chondrillina), introduced into Australia from the Mediterranean area by the cooperative effort of French and Australian plant pathologists, controls rush skeletonweed (Chondrilla juncea), a severe weed in wheat fallow in Southeast Australia.

The biology of the fungus, its specificity for rush skeletonweed and its epidemiology have been studied intensely in the Mediterranean area, the native land of the weed and the pathogen, before introduction of the pathogen into Australia. The fungus is highly specific for rush skeletonweed; it attacks all parts of the plant and at any stage of growth. Seedlings are especially susceptible and easily killed; older plants produce fewer seeds because of the pathogen. Climate in Australia has been favorable for spread of the pathogen and in two years it has become an epidemic. This rust may be a potential control for rush skeletonweed in the Western U.S.

A similar heteroecious rust (Uromyces rumicis) has effectively suppressed growth of curly dock (Rumex crispus) in Europe. Its biology and specificity at various growth stages on the weed have been demonstrated in Italy by ARS scientists. As with most rust diseases, this curly dock pathogen spreads over wide geographic areas by wind dissemination of the uredial or repeating spore stages. It reduces seed set, establishment of seedlings, and reduces vigor of older plants. This obligately parasitic fungus shows promise as a self-sustaining biocontrol agent for control or eradication of this severe pasture weed of the Southern U.S. The effect of the pathogen on its alternate host, Ranunculus ficaria or related ornamental ranunculaceous selections, has not been studied because the telial (overwintering) spores failed to germinate.

An anthracnose disease of Sesbania aegyptiaca was discovered in Uttar Pradesh, India, by two Indian plant pathologists. This pathogen was described as Colletotrichum sesbanae, but according to von Arx, it would be Colletotrichum gloeosporioides. Requirements for culture, biology, growth cycle, and specificity of this pathogen have not been determined. If this pathogen were specific to the genus Sesbania, it would be a potential mycoherbicide for Sesbania exaltata Cory., a problem weed in rice and soybeans in the Southern U.S.

Spiney cocklebur (Xanthium spinosum), a weed of pastures and fallow land in Australia, is damaged by the fungus, Colletotrichum xanthii. This pathogen dispersed in weedy areas, controlled this prickly weed. The fungus persisted and reinfested the weed in years following release. Culture requirements, biology, growth cycle, and specificity of this pathogen have not been examined. If the organism were specific at the generic level, it may be an effective mycoherbicide for common cocklebur (X. pensylvanicum), a problem weed of many crops in the U.S.

5 Antagonists of plant pathogens. U.S. plant pathologists have not made explorations in foreign areas for the specific purpose of acquiring or discovering antagonists with potential for biological control of pathogens. However, pathologists working in other countries have shown that certain native bacteria or fungi control local diseases in those countries, and those agents are now being imported to the U.S. for tests against pathogens here. Some specific examples:

a A hypovirulent isolate of the chestnut blight fungus, Endothia parasitica, was found effective against the blight in France, and is now under test at the Connecticut Agricultural Experiment Station; workers at that station confirmed the control of French isolates of the pathogen, but cannot demonstrate control of U.S. isolates of the pathogen.

b An avirulent mutant of the crown gall bacterium, Agrobacterium tumefaciens is now in commercial use in Australia where it controls crown gall in fruit trees if the tree seedlings are dipped in a cell suspension of the mutant as they are transplanted from nursery to orchard. This mutant strain is now under test in California where it also shows promise to control crown gall.

c Phialophora radicicola and Gaeumannomyces graminis var graminis were shown in England and Australia, respectively, to control the related wheat take-all fungus, G. graminis var tritici. Isolates of these two antagonistic fungi were imported to Washington State where greenhouse tests confirmed some control potential, but where field trials have been less encouraging.

d A strain of Bacillus subtilis that controls Rhizoctonia solani on wheat in Australia, and which also increased carrot and corn yields when introduced on seeds in Australia, has been imported into the U.S., (California) and has been shown to give some response on strawberry.

e A strain of Chaetomium globosum which provides a natural control of Helminthosporium victoriae on oats in Brazil entered the U.S. years ago on oat seed and was shown at Minnesota to control H. victoriaea on oats here, also.

B Visualized Technology

1 Parasites and predators. Determine whether effective parasites and predators exist in foreign countries, and increase the introduction and establishment of them in the U.S. The number of species to be established could probably be increased by 10%; that is

to about 12, within the next ten years at the current level of research effort.

Both the number of beneficial species introduced and established and number of target pests need to be drastically increased to more rapidly realize the potential benefits. During the past 10 years, 39 pest species have been the targets of ARS introduction programs. A recent survey by the ARS Working Group on Natural Enemies has identified a total of 123 potential target pests (or pest groups) for introduction programs. At the current level of research effort, the number of targets of introduction programs for the next 10 years could be increased only by about 10%, i.e., introduction programs could be mounted against about 43 target pests. However, of these, intensive introduction programs could be mounted against only about 5-10 target pests. In the past decade, over 200 beneficial species have been imported and 181 have been released from quarantine for field release or study. At current levels of research effort, both figures could possibly be increased by 10%, i.e., about 220 species could be imported, and 198 could be released from quarantine. (During the past decade many beneficial species have been imported as a result of PL 480 research overseas. The projected increases assume that PL 480 activities will continue at the same rate, which may not necessarily come to pass).

Currently anticipated intensive exploration and importation programs include introductions of natural enemies of lygus bugs, gypsy moth, greenbugs, and alfalfa blotch leafminer.

Lygus bugs. Reduce control cost of lygus bugs by 20% by establishing 2 parasites (10 years).

Gypsy moth. Establish 2 parasites and 1 predator against this pest and reduce the peaks of infestation in forest areas by 20%. (10 years) One or more of the parasites may be utilized in integrated pest management programs involving programed or mass releases.

Greenbug. Reduce control costs and damage losses of greenbug by 25% by establishing 2 parasites and 1 predator.

Alfalfa blotch leafminer. Reduce damage and control costs by 60% by establishing 4-5 parasites against this pest.

In addition to these initially planned intensive exploration programs other potential target pests identified by the ARS Working Group on Natural Enemies including cutworms affecting various crops, larval pests of soybeans, horn fly, face fly, green peach aphid, Mexican beetle, pear psylla, Sitona legume weevils, pea weevil and others will be considered on an opportunistic basis or may be substituted in lieu of the targeted pests.

Establish a system for publication of annual releases of natural enemies in the U.S. including computerized data storage and retrieval systems for letter documentation of establishment and evaluation of imported natural enemies (10 years); the effects of such systems would be to provide a means of tracking the results of importations.

2 Insect pathogens. Determine whether insect disease producing organisms effective against U.S. pests exist in foreign countries and evaluate them for possible introduction to the U.S.

At present there is no direct ARS effort on discovery of insect pathogens in foreign countries. Therefore, the objectives for the future cannot be reached other than through PL-480 research or that supplied gratuitously by foreign institutions and science exchange programs such as that with USSR. The results of such unstructured research are not predictable or dependable. The expanded effort indicated in Section E would place insect pathologists as members of the ARS laboratories in Europe, South America and Japan.

3 Weed biotic control agents except pathogens. Improved mechanism (e.g., periodic consultation between weed scientists and biological control personnel, etc.) for selecting target weeds; set of criteria for establishing priorities (e.g., potential and present losses due to weed, problem habitat, etc.) and determining the probability of successful biological control. Within the next 1-2 years, set up system for selecting and evaluating 5 target weeds/region of ARS, and locate weed specialists willing to cooperate on each weed species. Reevaluate listing every 5 years, adding new plants as needed.

Improved system of surveying, identifying, and cataloging the natural enemies associated with weedy plants (e.g., coordinated library, herbarium, and museum studies and foreign exploration); improved follow-up process for making preliminary evaluations. Under the improved system, complete the preliminary survey of 5 new target weeds every 5 SY's, and compile a listing of potential candidate insects for each weed species.

Improved host specificity study methods to avoid the possible rejection of safe biotic agents, and to increase the understanding of factors governing host selection; improved ability to estimate insect impact on the weed plant prior to introduction and to predict the interactions between various introduced control agents and those already present, to insure maximum suppression of the weed. This includes the ability to determine the physical, biotic, and ecological requirements of control agents to insure their establishment and maximum effectiveness in a control program. Under the visualized technology the average time and effort to certify a weed feeding insect as safe and effective for use in the U.S. could be reduced by about 40%, i.e., from 3.5 SY to 2 SY (5 years).

Improved method of measuring insect impact on the plant, the amount of control obtained, and the benefit derived from the various applied controls. This will add to the basic knowledge of how insects control plants and further aid in the preselection of candidate species.

In total, the visualized technology is one of improved definition of the problem weeds and increased availability of potential natural enemies better adapted to the problem habitats. A planned flow of work should improve the utilization of existing and/or expanded numbers of personnel and increase the output per dollar invested.

4 Weed pathogens.

a Reduce losses from rust skeletonweed by 50% by importation of *Puccinia chondrillina* rust (10 years).

b Reduce losses from curly dock by 20% by introduction of *Uromyces rumicis* rust (10 years).

c Reduce losses from hemp sesbania by 6% by introduction of anthracnose fungus, *Colletotrichum gloeosporioides* (10 years).

d Reduce losses from common cocklebur by 6% by introduction of anthracnose fungus, *Colletotrichum xanthium* (10 years).

5 Antagonists of plant pathogens.

a Determine whether biological agents (antagonists) for the control of plant pathogens exist in foreign countries and evaluate them for possible introduction to the U.S.

At present there is no direct ARS effort on discovery of pathogen antagonists in foreign countries. Therefore, future objectives cannot be reached except through informal contact with foreign scientists which is an unsatisfactory means of providing an effective research program. An expanded research effort would provide plant pathology expertise overseas and in quarantine laboratories for the evaluation of antagonists.

Some possible research objectives that could be attained with expanded effort include:

a Elimination of crown gall from California orchards and vineyards within 10 years by means of avirulent antagonists.

b Increased longevity of avocado and citrus orchards of Southern California through the suppression of phytophthora root rots by means of suppressive soil factors.

c Restoration of the chestnut as a major shade tree in the U.S. through suppression of Dutch elm disease and chestnut blight by means of mycoviruses of fungi, avirulent strains or hypovirulent strains of pathogens.

d Reduction of plant feeding nematode populations by importation of fungal pathogens.

C Research Approaches

1 Parasites and predators.

a Explore foreign countries for effective parasites and predators; increase introduction and establishment in the U.S.

i Determine whether effective native natural enemies of the pest exist in the U.S., and whether additional natural enemy niches need to be filled to reach more effective levels of control.

ii If pest is of foreign origin, determine probable center of foreign origin using existing and new biological taxonomic information, and explore foreign area(s) for pest and its natural enemies.

iii Discover the natural enemies of the pest in the foreign area(s) and their taxonomic identities, and determine their biology, ecology, and effectiveness by means of field exploration and field and laboratory studies; determine secondary parasites affecting their effectiveness.

iv Determine whether the ecological requirements of the natural enemies in the foreign area(s) correspond favorably with conditions existing in this country.

v Determine whether promising natural enemies are host specific or otherwise will not adversely affect beneficial species in the U.S.

vi Develop means to collect or rear chosen exotic natural enemies in adequate number for colonization in the U.S.

b Improve methods of determining whether exotic natural enemies are free of all potentially detrimental material and devise new means of effecting release and establishment of the beneficial species in the U.S., including initially, for example, studies on lygus bugs, gypsy moth, greenbug, and alfalfa blotch leafminer. (Sevres, France; Sapporo, Japan; Hurlingham, Argentina; NER-Newark, DL, Beltsville, MD; NCR-Columbia, MO, WR-Tucson, AZ).

i Identify the exotic species and eliminate any secondary parasite, pest species, or plant material under quarantine conditions to prevent inadvertent release of detrimental materials.

ii If not determined overseas, determine whether the beneficial species are host specific or otherwise will not adversely affect other beneficial species in the U.S.

iii Conduct biosystematic studies of exotic natural enemies to aid in making decisions to release and in developing means to establish and manage them in the U.S.

iv Develop means to rear exotic natural enemy species in large numbers for field colonization if possible and feasible.

v Determine optimum areas and conditions to release and effect establishment of exotic natural enemies in the U.S.; develop cooperative programs with other federal agencies, SAES, universities, etc., to aid in establishment of the beneficial species.

c Evaluate and increase the effectiveness of established exotic natural enemies. (NER-Newark, DL, Beltsville, MD; NCR-Columbia, MO, WR-Tucson, AZ).

i By detailed field study, evaluate effectiveness of the established beneficial species in their new environment and document their dispersal.

ii Aid in the dispersal of established beneficial species by effecting subcolonization of the species in other areas by collection and direct release in other areas or by releases through increased cooperative activities with other federal agencies, SAES, universities, state departments of agriculture, commercial concerns, and other interested organizations.

iii Determine how effectiveness of the established species can be enhanced by other means to regulate pest populations below economic injury levels.

iv Determine cost-benefit ratios of natural enemy importation programs.

d Develop means to document the release, establishment, and effectiveness of natural enemies in the U.S. (NER-Newark, DL, Beltsville, MD; NCR-Columbia, MO).

i Develop for publication and dissemination an annual record of released beneficial species in the U.S. for the benefit of U.S. taxonomists and biological control workers; from resulting feedback information from various field stations involved, develop computerized system of recording and following the permanent establishment, dispersal, and effectiveness of exotic species.

ii Develop system of documenting the identity of exotic species released in the U.S. by voucher specimens representing released material, for current and future study by taxonomists and biological control researchers.

2 <u>Insect pathogens</u>.

a Explore foreign areas for entomopathogens occurring on U.S. pests and related species. (None).

b Identify and culture entomopathogens for host specificity (NER-Beltsville, MD; NCR-Columbia, MO).

c Determine degree of hazard to public health if entomopathogens are introduced to the U.S. (None).

d Evaluate effectiveness against intended host and related species (NER-Beltsville, MD; NCR-Columbia, MO).

3 Weed biotic control agents except pathogens.

a Selection of target weeds (WR-Albany, CA; SR-Temple, TX; Stoneville, MS; Gainesville, FL; Ft. Lauderdale, FL, NER-Beltsville, MD).

i Develop closer liaison with federal and state weed personnel to increase their input into:

a Drawing up lists of potential weed candidates throughout the U.S.

b Determining the damage caused by the candidate weeds (e.g., crop loss, poisonous, etc.), their distribution and potential spread, etc.

c Resolving conflicts of interest, i.e., help weigh the noxious characteristics of each weed against its usefulness as food and shelter for wildlife, erosion control, etc.

d Ascertaining the degree of control desired in problem areas.

e Assessing the probability of finding host specific and effective natural enemies.

f Developing criteria to help in setting priorities for work projects.

b Increasing the availability of potential control agents (all locations listed in "a" plus overseas laboratories in Europe, South America and Japan).

i Improving efficiency of system for conducting literature, herbarium and museum studies, and field surveys for the natural enemies of weeds (e.g., coordination of efforts in the U.S. and overseas). Increasing the network of foreign and domestic cooperators capable of studying the weeds throughout the world, and collecting and recording their insect enemies.

ii Coordinating the curating and identification of collected materials and compilation of host records.

iii Coordinating background search (e.g., literature, correspondence, museums, etc.) to determine likely candidate species.

iv Map the distribution of the various target weeds in North America and throughout the world. Note morphological and growth variations in plants and pinpoint the origin of pest species. Characterize the plant habitats in the primary and secondary areas of distribution and otherwise develop information along the lines listed by Cavers and Mulligan, Can. Jour. Plant. Sci. 52:651-4, 1972. (See NRP 20280, Tech. Objective I). This work would be aimed at ascertaining the natural stresses acting upon the plant, the role of natural enemies

in accentuating these stresses, and in general serve as background for the selection of potentially effective weed control insects.

Also in predetermining which insects will have the greatest potential effectiveness, we need to answer the following questions:

a How do insects damage plants?

i Examine insect damage to plant. Section and identify affected tissues. Note when damage occurs.

ii Determine role of affected tissues in plant development cycle and quantify effects of damage.

b How do insects control plants?

i Determine productivity of plant under various conditions within its geographic range.

ii Determine the influence of environmental factors on the growth and productivity of the plant.

iii Determine the reproductive potential of insect under given conditions and estimate population levels that could be achieved.

iv Determine factors inherent in insect's behavior that may limit its buildup.

v Develop a predictive model of plant growth and insect buildup to aid in determining effectiveness of insect.

c Insect host plant selection studies (all locations listed in "b" above.

i Record behavior of insect in the presence and absence of the host plant and/or other plants.

ii Record the behavior sequence of each insect during host finding and acceptance.

Determine which factors are of importance in host selection and rejection. These studies will be aimed at improving the screening process to avoid the rejection of otherwise suitable species.

Many aspects of the evaluation process can be done in domestic quarantine laboratories. However, work in foreign areas is sometimes preferable. Work in the native range of the weed and insect provides freedom to study the biology and ecology of each agent and its effect on the host plant under natural conditions free from the restrictions of the laboratory. In some cases the work can be done more cheaply in foreign labs.

d Post release studies (WR-Albany, CA; SR-Temple, TX; Stoneville, MS; Gainesville, FL; Ft. Lauderdale, FL; NER-Beltsville, MD).

Develop suitable techniques for sampling plant abundance and range and measuring subsequent changes in the plant community, e.g., transects, infrared photography, etc. Measure plant productivity in the presence and absence of control agents (e.g., exclusion cages, insecticidal checks, etc.) and in different areas of each weed's range.

4 Weed pathogens.

a Increase the survey effort of foreign weed pathogens; select for study genera with high potential as weed-control agents (None).

b Increase the rate of introduction and evaluation of foreign weed pathogens. Prime targets are *Puccinia chondrillina* rust of rush skeletonweed, *Uromyces rumicis* rust of curly dock, *Colletotrichum gloeosporioides* anthracnose fungus of *Sesbania aegyptiaca* for possible use for control of *S. exaltata*, *Colletotrichum xanthii* of *Xanthium spinosum* for possible use for control of *X. pennsylvanicum*, and other promising weed pathogens discovered in the surveys (NER-Frederick, MD; SR-Stoneville, MS).

c Expand research on biology of foreign weed pathogens to include host specificity, host-pathogen relationships and interactions, life cycles of promising weed pathogens, culture, growth requirements, and mass production of inoculum (NER-Frederick, MD; SR-Stuttgart, AR).

5 Antagonists of plant pathogens.

a Seek avirulent mutants and strains in habitats where the pathogen and host to the pathogen are native and occur in wild populations; collect an array of types; test for avirulence under controlled conditions; test for possible virulence to related host plants; import to the U.S. and test further in both the greenhouse and the field (None).

b Seek pathogen-suppressive soils internationally through cooperation of foreign research agencies. Many such soils are already known, for example, in Australia to *Phytophthora cinnammi*. If the suppressive factor is tolerant of 70-80° C moist heat (e.g., spore-forming bacteria), treat soil at 60° C 30 minutes to remove pathogens, then import soil for further purification and testing of responsible agents. If not heat-tolerant, treat soil or sieve soil in other ways to remove pathogens (None).

c Seek nematode-trapping fungi or endoparasites of nematodes in sites where nematode diseases are minor, or in the native habitats of plant hosts of phytophagous nematodes, or from foreign research agencies with such fungi already under test (None).

D Consequences of Visualized Technology

1 Parasites and predators.

a Increase production of food and fiber and protection of forestry products by improved biological control of target pest.

b Reduce the costs of producing food, fiber, and forestry products by reduced costs of insect control.

c Increase income of producers of food, fiber, and horticultural and forestry products.

d Make it possible for U.S. to provide larger share of food for world population and increase export profits.

e Reduce environmental pollution through reduction in total need for application of insecticides.

f Reduce expenditures of energy required to produce petroleum-based insecticides and of energy required to apply insecticides.

g Reduce effects of insecticides on nontarget organisms such as native beneficial insects, and thereby increase effects of natural control.

h Decreased pesticide sales for industry.

i Develop new industry for the production and utilization of parasites and predators in insect control.

j Increase cooperation between federal and state pest control programs.

k Develop systems approaches to integrated pest management that will make maximum effective use of natural enemies.

l Provide safe methods for utilization of natural enemies and related methods to control pests.

m Provide basic reference information on biological control agents applicable to all pest insects and their control.

2 Insect pathogens.

a Increase production of food and fiber and protection of forestry products by improved control of pests.

b Reduce costs of producing food, fiber, and forest products by reducing costs of insect control.

c Increase income of food, fiber, and forest producers.

d Make possible increased U.S. exports of food.

e Decrease environmental pollution by reduction of chemical insecticide applications.

f Decrease energy expenditures through reducing need for chemical insecticides.

g Reduce sales of chemical insecticide producers.

h Develop new industry for production and utilization of entomopathogens in insect control.

3 Weed biotic control agents except pathogens.

a Assure the selection of priority target weeds for which there is a high probability of achieving control.

b i Increase the availability of potentially effective weed-feeding insects on a wider range of weed pests and at a reduced cost per insect.

ii Provide detailed biological information about weed pests essential not only to the selection of effective natural controls, but also to the development of compatible integrated control programs.

c Improve the understanding of factors influencing plant abundance and distribution. Also aid in assessing insect pest damage to crop plants.

In addition, the increased implementation of current and visualized technology will:

i Reduce the use of chemical and other artificial weed control methods. As a consequence, this will:

a Reduce weed control costs.

b Reduce possibility of chemical residues.

c Minimize environmental upset.

d Reduce use of nonrenewable resources (energy and raw materials to manufacture chemicals, etc.).

e Reduce sales of pesticide industry.

ii Improve the production economics of pasture, range and aquatic habitats, and other areas where weeds are a problem.

iii Allow for an increased plant diversity by selectively removing dominant weedy species. This in turn will increase the diversity of wildlife, bees and insects, and other organisms, etc.

iv Remove selected plants from the environment, reducing the numbers of wildlife, bees and insects, and other organisms.

v Permit replacement of the target weed with other weed(s).

4 Weed pathogens.

a Control weeds resistant to chemical herbicides.

b Control weeds in areas where chemical control is not economically feasible.

c Reduce crop injury from chemical herbicides.

d Improve crop yields and quality.

e Reduce the cost of weed control.

f Conserve water in dry environments.

g Reduce the cost of chemical herbicides.

h Reduce environmental and crop pollution from chemical herbicides.

i Decrease chemical herbicide industry income.

j Decrease habitat/food for some nontarget animals, insects, and birds.

k Create new mycoherbicide industry.

l Develop new information on fundamentals of pathogen-host relationships.

5 Antagonists of plant pathogens.

a Reduce or eliminate the need for certain fungicides, bacteriocides, or nematocides.

b Provide a means to control certain wilt and root rot diseases where presently no host resistance, cultural, or other control exists; control of such soilborne pathogens would greatly improve productivity of the host crop.

c Certain processing crops, e.g., fresh peas, or certain tomato varieties, preferred by the industry and the customer, but presently replaced by less palatable varieties with necessary resistance to *Fusarium* wilt could again be grown if a good biocontrol of *Fusarium* were developed.

d Where avirulent strains related to pathogens are used, the risk exists that reverse mutations, or synergism with the pathogen on other unexpected host crop could contribute to increased disease in some situations.

E Potential Benefits

1 Parasites and predators. It is difficult to assess the annual net benefits to farmers and other producers of food, fiber, and horticultural and forestry products through increased production resulting from increased successful biological control of pests by introduction of natural enemies. In many cases the benefits may be reduction in pesticide pollution of the environment.

However, recent figures give an indication of the annual savings to accrue through reduction in application of insecticides only, as a result of successful biological control by introduction of natural enemies. The successful biological control of the alfalfa weevil in New Jersey has resulted in an estimated 80% reduction in the acreage sprayed for the pest in that State in 1975. Based on an average cost of $5 per acre for chemicals and labor, the savings resulting from reduction in treatment is calculated to be $244,000 for New Jersey alone in 1975. Savings due to reductions in acreage treated, ranging from 20% to 100% reduction in 12 States including New Jersey, where exotic natural enemies of the alfalfa weevil are established, are estimated to be over $7,000,000 in 1975. Those figures do not consider savings in the costs of production of the insecticides or savings in the use of energy to apply them, nor are benefits of reduced environmental pollution considered.

Both the benefits to accrue through increased production and reduced damage and those associated with reduction in insecticidal treatments are long term and, most importantly, cumulative. Once effective exotic natural enemies are introduced and established, they become self-perpetuating control agents, requiring no additional efforts by man to continue their control action, and the benefits of their control accrue annually.

Considering the cumulative benefits due to reduced treatment costs and damage, it has been estimated that biological control importation programs will easily return $30 in benefits for every $1 spent on a program for the introduction of natural enemies. Even assuming a projected 25% success rate (for complete or substantial control) over the next decade, which can be expected without an expansion of current efforts, instead of the optimum 40% rate, an estimated $18.75 return for every $1 invested in the ARS natural enemy importation program can be expected, an extremely favorable ratio (this compares well with the estimated $5 benefits for each $1 spent in development of new insecticides). Actually, benefits would be even greater considering the unmeasurable benefits accruing from only partially successful programs.

Lygus bugs. In a single year in California, control costs alone for this pest were estimated at $20,161,703 and, in addition, yield loss at $36,669,523 (Calif. Dept. Food, Agric., Est. Damage/Crop Loss by Insect/Mite Pests 1974. Sacramento, CA, 1975. 14 p.). Estimates for the whole U.S. could easily exceed $150 million. By reducing costs of present control by 20% with parasites as envisioned, within 10 years the annual control cost reduction for California would approximate $4 million and $30 million nationally. These savings would be cumulative and lend increased credibility to the 30:1 benefit/cost ratio mentioned in the Current Technology of this NRP.

Gypsy moth. Although 3 studies are underway to determine the losses due to this pest, no data are available now. Preliminary results indicate that the full effects of infestation may be delayed for as long as 7 years at which time tree mortality is often high. Other consequences of defoliation by this pest involve aesthetic and nuisance values on residential and recreational areas which the public holds in higher regard than the woodland areas. If a modest $20 per acre damage is allowed for the 750,000 acres defoliated in 1974, the result of a 20% reduction with parasites and a predator would amount to $3 million per year.

Greenbug. The control costs and damage losses for this pest on wheat in Kansas, Nebraska, Oklahoma, South Dakota and Texas in 1976 were estimated at $133 million. The long term average annual loss has been estimated at $40 million. The discovery, introduction, and utilization of 2 parasites and 1 predator during the next 10 years could reduce the more conservative estimate by 25% or $10 million annually. An expanded research effort might provide these benefits in 5 years with a gross return of $50 million. Likewise, when 1976 damage loss and control cost estimates ($25 million for this pest on sorghum) are used, the visualized technology could return at least $6 million annually.

Alfalfa blotch leafminer. Severe infestation of this insect can cause complete loss of an alfalfa cutting. In Massachusetts in 1969-70 a 10% average infestation was estimated to cause a loss of about $9/acre in yield. In addition, one leafminer per leaf can cause a protein reduction of 16% in that leaf. Thus, a 25% infestation (a common level) causes a 4% loss of protein in the harvested hay and a yield loss of $22/acre (in 1970 dollars). The effect of establishing new parasites of this pest could reduce these losses by 60% or approximately $13 per acre in yield alone.

Increased potential benefits if efforts were increased in the biological control importation program are discussed under Research Effort: Expanded Level.

2 Insect pathogens. The potential benefits from introduction of exotic entomopathogens cannot be estimated until more is known of the organisms which occur in foreign countries. Since some species of the genus *Heliothis* occur in every continent, it may be assumed that each is infected with bacteria, viruses, and other entomopathogens.

The exploration phase of research under this TO, conservatively, may double the number of organisms available for use against such pests as the bollworm or corn earworm and the tobacco budworm. Similar potential may exist for other lepidopterous pests, grasshoppers, and mosquitoes. It is possible that microbial insecticides may replace chemical pesticides.

3 Weed biotic control agents except pathogens. A total of 30 weed-feeding insects has been introduced to the U.S. (14 of which were studied in detail by USDA personnel) during a research span of 50 SY's (total work years of U.S. personnel stationed at overseas posts) for an average of 3.5 SY's/insect. On the basis of $80,000/foreign SY this would be a reduction in overseas' cost per insect from $280,000 to $160,000 if the average SY's/insect were reduced to 2.

Weed control with natural enemies will vary depending on the availability of suitable organisms and the problem habitat. A weed occurring in several habitats will have different stresses placed upon it according to the habitat. These stresses will in turn affect the productivity and time of plant growth in different ways, as well as influencing the innate capacity for increase of the control agent (once the latter's presence is assured). Thus, it is difficult to predict with any degree of accuracy the potential outcome of any given project.

However, by reviewing the past record of biological control obtained in various projects, it is possible to make some estimate of probable future success. For this purpose, information from a table summarizing the biological control of weeds program in Hawaii was analyzed. Releases made at approximately 40 sites against 16 species of weeds were rated as to degree of success, i.e., complete, substantial, partial, ineffective.

Table 2. Rating of biological control of weeds release sites in Hawaii, 1902-75

5	- complete control	80-100% control of weed
5	- substantial control	40-80% control of weed
23	- partial control	20-40% control of weed
7	- ineffective control	0-20% control of weed
40	release sites total	

The results suggest that any particular project will have an 82% probability of attaining status as either a partial, substantial, or complete success. Within this broad category there would be a 70% chance of being partially successful, and a 30% chance of being substantially successful.

These figures can be extrapolated to future projects to aid in predicting potential benefits. For example, in the musk thistle project now in progress, this weed is estimated to cover over 2 million acres. The current recommended control costs $6.00/acre. Thus, a 30% reduction in acreage (600,000 acres) could produce a savings of $3 million/year in control costs alone. Similar estimates could be developed for other projects once the acreage and cost of the weed were known.

4 Weed pathogens. Rush skeletonweed already affects considerable acreage of rangeland in certain Western States - mainly Idaho, California, and Washington where an estimated 1.6 million acres are infested. This weed is a potential threat to an estimated 5 to 6 million acres of small grain crops (wheat, oats, barley) in Western States; in Australia competition from skeletonweed commonly reduces small grain yield by 50%. In California alone the State Government is spending $75,000 annually in control programs.

The rust fungus has successfully controlled skeletonweed under Australian conditions after 3 or 4 years. It reduced vigor, stem growth, seed production of weed plants, increased wheat yields, and reduced the use of herbicides used for control.

During the next 10 years we might expect field releases of the rust to give comparable control of skeletonweed in the U.S. to that experienced in Australia; research indicates that skeletonweed clones from the Western U.S. are damaged by the rust fungus. Successful control with the rust fungus would eliminate the need for state control programs, improve production of rangelands, and prevent infestation and losses of grain crops.

Curly dock is a problem weed throughout the U.S. In 1968 it was listed among the top 5 most damaging weeds of annual and perennial pastures in 13 States; in 8 States more than 40% of the pasture acreage was affected by curly dock. Also, production of milk and meat from animals grazing on infested land is frequently reduced in quality because of off-flavors from feeding on dock plants. Five States in the Southern U.S. reported that curly dock affected a total of 360,000 acres of small grains in 1968. Reasonable success with the introduction and spread of the curly dock rust fungus would reduce losses in yields of pastures and small grains. It is estimated that in the next 10 years successful development of this rust could reduce losses from curly dock by 20%.

Hemp sesbania causes losses estimated at $15 million annually in rice and soybeans in the South; common cocklebur losses are estimated at $100 million annually in soybeans, cotton, and grain sorghum. Importation and development of fungi (*Colletotrichum gloeosporioides* for hemp sesbania and *C. xanthii* for common cocklebur) to control hemp sesbania and common cocklebur could be an important tool of a weed management system for control of these weeds. In the next 10 years commercial development and use of fungi for control of these two weeds could contribute to a savings of 5-6% in reduced losses from these two weeds.

5 Antagonists of plant pathogens.

a Crown gall is presently a multimillion dollar disease in California orchards and vineyards; its control by the avirulent antagonist to the virulent form would eliminate that loss.

b Phytophthora root rot is the number one root disease of avocado and citrus in Southern California; control by the suppressive soil factor from Queensland, Australia, would lengthen longevity of the orchards.

c Root disease problems caused an estimated 900 million dollar loss to soybeans in the U.S. with one major pathogen being Phytophthora megasperma var sojae. Control of this pathogen alone would make considerable inroads into soybean losses with resultant improved yield and greater export product.

d Control of the chestnut blight fungus by hypovirulent relatives of the pathogen could restore stands of this prized hardwood tree, now nearly extinct in the U.S. Similarly, control of the Dutch elm disease by an antagonist injected into the trunk could save this magnificent tree species from doom in the Midwest.

e Control of the take-all disease by introduced fungi could save the U.S. wheat industry at least 10-20 million dollars annually.

F Research Effort

1 Parasites and predators. The addition of new ARS research and support personnel, and the use of new or expanded facilities would make it possible to accelerate the introduction of natural enemies to combat pests in the U.S. over that expressed under the section "Visualized Technology."

An expansion of ARS biological control exploration and research overseas could be accomplished by: (1) Consolidation of the two ARS European biological control laboratories now in Italy and France; (2) Augmentation of the staff of the overseas laboratories (an increase of 5 SY's and 17 support personnel), to expand exploration and research throughout Europe and Asia, and provide regular funding for Asian operations; (3) Provision for temporary satellite stations in connection with the overseas laboratories for on-the-site research of limited duration in Eastern Europe, the Near East and South Asia, and Africa; (4) Funding of an ARS biological control laboratory in South America currently supported solely by the U.S. Corps of Engineers and augmentation of its staff (addition of 2 SY's and 2 support personnel) to allow exploration and research in South America; (5) Establishment of a permanent fund to support TDY exploration by domestic workers in areas beyond the scope of the foreign stations and for work by domestic workers at ARS foreign stations, and contracts for collection of natural enemies by foreign or international organizations.

With increased ARS effort overseas, expansion of domestic quarantine, release, establishment, and evaluation activities and distribution of natural enemies to other Federal and State cooperators could be accomplished by: (1) Continued support of the 1 SY and 1 technician now funded by "Gypsy Moth Funds" (through FY 1977) and addition of 2 SY and 3 support personnel to quarantine facilities; and (2) Addition of 1 SY and 1 technician for documentation activities.

	Total ARS Expanded Level	
	SY	Support
Foreign 1/	6	18
Domestic 1/	3	4
	9	22

1/ Plus assumption of funding in FY 1978 of 1 SY and 1 technician currently funded by special "Gypsy Moth Funds."

The increased overseas and quarantine efforts would necessitate a marked increase in the number of ARS biocontrol workers in each Region working on commodities or groups of commodities to bring introduced biocontrol agents to the point of establishment and to demonstrate their potential effectiveness.

The increases in ARS personnel involved in the exploration, quarantine, distribution, release and establishment activities of the natural enemy importation program would also necessitate an increase in the number of cooperators from other ARS facilities and from other Federal agencies (APHIS, FS), SAES, universities, and State Departments of Agriculture, etc.

Potential benefits of an accelerated effort. With increases in ARS effort, and assuming the same level of PL-480 activity of the past decade, the number of target pests chosen and the rate of introduction and establishment of exotic natural enemies could be doubled in some aspects, i.e., the Visualized Technology could possibly be achieved in 5 years instead of 10. However, since this is a continuing program, it is important to express expanded levels of programs in terms indicating its continuous nature. Therefore, it is estimated that the expanded level of effort would permit the importation of 2 times the number of beneficial species (about 400) and the release from quarantine of 1.5 times the number (about 270) in the next 10 years, as opposed to the projected numbers to be imported (220) and released (198) expected under current levels of research efforts. With increased numbers of species released, the number of species to be established should be at least 1.5 times (18) the number expected under current levels of efforts.

Most important, however, the increased effort should result in a rise in the number of complete or substantial successes in the biological control of pests to approach the worldwide capability of 40% of all attempts (as opposed to an expected 25% under current level of effort). This is especially true since a greater degree of concentration on selected pests would be possible. This increase would increase expected benefits to the optimum of $30 for which $1 expended on the natural enemy importation program, to which should be added the unmeasurable benefits accruing from partial successes in controlling target pests which should also increase in number.

	Year	Current Support SY's	Current Support Gross Dollars	Expanded Effort [1] SY's (ARS Only)
ARS	FY76	11.5	1,061,975	20.5
SAES				
Other				
Total		11.5	1,061,975	20.5
Years required for ARS to achieve the Visualized Technology			10	5

1/ Includes base and additional SY

2 Insect Pathogens

	Year	Current Support SY's	Current Support Gross Dollars	Expanded Effort SY's (ARS Only)
ARS	FY76	0	0	4
SAES				
Other				
Total		0	0	4
Years required for ARS to achieve the Visualized Technology			10	

3 Weed biotic control agents except pathogens

	Year	Current Support SY's	Current Support Gross Dollars	Expanded Effort [6] SY's (ARS Only)
ARS	FY76	8.3	451,300[1]	17
SAES	FY76	3.2	190,000[1]	--
Other		2.5[3]	194,400[1],[2]	--
		14.0	825,700	17
Years required for ARS to achieve the Visualized Technology			52.5 SY's[4]	30 SY's[5]

1/ Estimated figures
2/ Non ARS funding
3/ ARS SY's, but on soft money
4/ Based on objective of controlling 5 weeds (3 insects/weed) over next 10 years with current clearance time of 3.5 SY's/insect.
5/ Expanded support clearance time 2 SY's/insect.
6/ Includes base and additional SY

Facility Needs

	Laboratory space (ft^2)	Office space (ft^2)	Greenhouse space (ft^2)
Western Region	1500	300	1600
North Central Region	500	150	300
Southern Region	Renovation of quarantine spaces		
Japan	800	150	1000

4 Weed pathogens

	Year	Current Support SY's	Current Support Gross Dollars	Expanded Effort 1/ SY's (ARS Only)
ARS	FY76	1	50,000	4.0
SAES	FY76	0	0	--
Other	-	-	-	--
Total		1	50,000	4.0
Years required for ARS to achieve the Visualized Technology			10	5

1/ Includes base and additional SY

To obtain the Visualized Technology within a 10-year period SY's should be increased to 4. Significant effort should be devoted to foreign surveys of weed pathogens; primary evaluation of promising pathogens discovered in the surveys can be conducted at present biological laboratories in Hurlingham, Argentina; and Rome, Italy; and at the ARS Plant Disease Laboratory, Frederick, Maryland.

5 Antagonists of plant pathogens

	Year	Current Support SY's	Current Support Gross Dollars	Expanded Effort SY's (ARS Only)
ARS	FY76	0		3.0
SAES	FY76	1.0		
Forest Service	FY76	0		
Industry	FY76	0.5		
Total		1.5		3.0
Years required for ARS to achieve the Visualized Technology			10	

III.2 New and improved technology for increase and conservation of introduced and native biological agents for control of insects, weeds, plant pathogens, and other pests.

A Current Technology

1 Parasites and predators. There is ample evidence demonstrating the value of foreign exploration and importation of entomophagous insects for control of pest insects and related arthropods. However, it is also clear that this method is most promising in perennial-type crops and least promising in short-term single cropping systems. It is the latter system that is most responsible for producing food and fiber for man. Fortunately, indigenous predators and parasites are an effective force (albeit reduced in monoculture agroecosystems) in the environmental resistance to increases in pest insect numbers.

Man's activities frequently increase pest incidence and severity by reducing ecosystem diversity, decreasing permanency, increasing productivity, and increasing crop immaturity. These practices discriminate against all arthropod diversity, but those plant feeders that are present exist in an abundance of food. Entomophagous insects frequently require food sources other than the host for completing development. They are deprived of refuges, alternate hosts/prey, pollen, honeydew and other requisites necessary for survival and reproduction. Pesticides applied for pest-insect control also kill the parasite/predator and eliminate the food supply to those that remain, thereby releasing their host/prey which resurge from foci located throughout the ecosystem. Additionally, outbreaks of secondary pests and elevation of previously innocuous species to pest status may occur.

Entomologists have responded to this phenomenon by developing an integrated approach to pest control utilizing several pest control measures to maintain pest populations at subeconomic levels. A common component of these programs involves conservation of predators and parasites through establishment of thresholds and using "selective" chemicals at the lowest possible rates. Timing and placement of chemicals to avoid contact with nontarget organisms have been used to advantage in several instances, e.g., seed treatment, treating selected parts of plants, use of systemics, etc. These methods may still reduce natural enemies by eliminating their food or even kill them as in the case of systemics.

Through the use of resistant plant varieties pest growth and reproduction may be reduced, thereby allowing natural enemies to reduce them prior to reaching the economic threshold. However, it has also been shown that the plant on which the host is feeding may affect host selection, fecundity, and longevity of the parasite.

Biological control by augmentation (periodic mass releases) has been demonstrated as technically feasible in several instances and is used on a "commercial" basis in several countries, most notably the USSR. This method of control is used on a limited commercial scale in the U.S., mostly in California for control of citrus pests. Models demonstrating the efficacy of this approach have recently been developed and verified, in part, for lepidopterous pests, aphids, and flies. The following are some examples: (1) mass release of the egg parasite *Trichogramma pretiosum* controlled 3 lepidopterous pests in tomatoes: (2) mass release of lacewing eggs and larvae in cotton fields reduced "bollworm" populations; (3) inoculative releases of predaceous mites in apple trees controlled phytophagous mites; (4) inundative releases of a pupal parasite controlled house flies; and (5) periodic releases of an exotic tachinid parasite controlled sugarcane borer larvae in sugarcane in Florida. Releases of both the pest and natural enemies have worked in a few instances and inoculating crops with pest adults or eggs alone increased parasitization. The primary obstacles to usage of these techniques are economics and lack of technology for large-scale insect production. Further, additional fundamental information is required on the host-parasite/predator relationships, density relationships, and methods for timing releases.

Production of parasites and predators has interested biological control workers since about 1930. Examples of parasites and predators that are reared or field collected for release on a commercial basis are as follows: *Metaphycus*, *Aphytis*, *Trichogramma*, *Leptomastix*, *Cryptolaemus*, *Chrysopa*, and *Hippodamia* species. Detailed analysis of cost of rearing parasites and predators are generally nonexistent. However, an automated system has been developed by ARS (College Station, TX), for experimental production of *Trichogramma* spp. on host eggs for $8.00/million. Methods were developed for aerial release at the rate of 300,000 parasites/acre for $8.40. Examples of other insect parasites and predators considered by ARS for large-scale production and release are as follows: *Lixophaga diatraeae* (sugarcane), *Pediobius foveolatus* (soybeans), *Spalangia endius* (muscoid flies), *Chrysopa* sp., and *Microplitis croceipes* (cotton), *Jalysus spinosus* (tobacco), *Amitus hesperidum*, and *Prospaltella clypealis* (citrus). Additionally, parasitic nematodes have been mass produced in the laboratory and used for augmenting natural populations. One mermithid nematode, *Reesimermis nielseni*, is being considered for marketing under the label "Skeeter Doom" for mosquito control. Further impetus to research with parasitic nematodes was received recently when EPA tentatively ruled that parasitic nematodes were exempt from FIFRA regulations.

Genetic deterioration commonly occurs when insects are mass cultured leading to loss of behavioral traits essential to the effectiveness of released parasites and predators. Thus, rejuvenation is periodically required by integrating field collected material into the culture. However, successful mass rearing of parasites and predators for release is dependent on developing methods for maintaining and measuring the quality of the produced insects.

Development of artificial diets would facilitate economical mass production of many parasites and predators. Research conducted within the past 10 years in France, Canada, and the U.S. has demonstrated the feasibility of in vitro rearing techniques (using semisynthetic media for rearing insect parasites and predators). However, manipulation of the beneficial immatures is required and no host surrogates have been developed which adequately simulate the natural host in all required respects. An artificial diet and rearing method were successfully developed for large-scale experimental production of the predator, *Chrysopa carnea*, but most predators are produced on live or dead host material.

Conservation of natural enemies may be accomplished by habitat modification or management. Examples of this method are as follows: (a) grain sorghum planted with cotton served as an area for natural enemy buildup and later dispersal into adjacent cotton strips; (b) wooden boxes around tobacco fields served as nesting sites for predaceous wasps, *Polistes* sp., resulting in lower hornworm populations; and (c) quick flowering mustards interplanted with cole crops served as a food source for a braconid parasite resulting in a 6-fold increase in parasitization of *Pieris* spp. larvae.

Supplementary foods have been experimentally provided in crops and used to retain, to arrest, to attract, and to sustain natural enemies when natural prey populations are low or where nonprey food such as pollen and honeydew is lacking. These foods were provided in the form of pollen, sunflower seeds, sucrose solutions, and yeast hydrolysates or Wheast® (a dairy product) in combination with sugar.

Selective breeding of entomophages resulting in more efficient development on nonhabitual hosts and change in temperature response has been accomplished in the laboratory. However, few cases have been reported where selective breeding was used on a practical basis.

Kairomones associated with host or prey are a vital part of the host or prey-finding process of entomophagous insects. This finding process involves an orderly sequence of behavior acts (fixed-action patterns), each of which must be released by an adequate amount of the appropriate stimuli. Therefore, effective performance of an entomophage in a target area requires the proper quality, quantity, and distribution of these stimuli. The primary stimuli involved are kairomones emanating from the host or prey and present in frass, moth scales, and/or other products associated with their presence in an area. Recent studies have demonstrated that we have the potential for identifying these kairomones, producing them synthetically, and incorporating them into management programs to enhance and ensure the effective performance of entomophagous insects.

2 Insect pathogens. These are microorganisms that either cause disease in insects or produce substances toxic to them. About 500 viruses, 1000 protozoa, 500 fungi, 100 bacteria, and a dozen rickettsia have been found in insects. In addition, over 35 insecticidal toxins are

known to be produced by bacteria, fungi, or actinomycetes. Scientists in ARS and State Agricultural Experiment Stations have been studying these organisms for over 25 years. Their work has led to the development of two highly successful commercial products from bacilli (bacteria which can be identified because they form a spore within their cells); (1) spore powders of B. popilliae, active against the Japanese beetle by causing a disease within the grubs; and (2) formulations of the "δ-endotoxin" produced by B. thuringiensis (BT), which are toxic to the larvae of many kinds of moths and butterflies (major feeders on many crops and forests). More recently, formulations of a virus infective to the bollworm of cotton and the tobacco budworm, two major species of Heliothis, have been developed.

Although effective formulations of B. popilliae can only be produced by infecting grubs of the Japanese beetle, ARS scientists had, by 1935, developed a means of producing the bacillus economically enough for practical use and had demonstrated that the formulations could reduce populations of the beetle. Between the years 1939 and 1953, 109 tons of spore powder of this bacillus were applied to over 194,000 sites in 14 States in the Northeastern U.S., and between 1954 and 1975, another 260 tons were used. Wider use could occur if the bacillus could be produced by normal fermentation processes, but so far no way has been found to grow the bacillus and produce infective spores without the insect.

One microbial insect control agent is being produced commercially in submerged fermentations -- the δ-endotoxin of BT. While the bacterium had been known since 1902, it was not until 1968, when ARS scientists developed new, more potent formulations of this insecticidal substance that it gained widespread use. In 1968 production was Ca. 13 tons per year. Now, 1,000 tons of formulations (valued at $8 million) of this toxin are being produced each year for the control of lepidopterous larvae in the U.S.

During 1963-1975, Baculovirus heliothis was tested in 20 States, Canada, Africa, Mexico, South America, Europe and Asia. Most of the tests were for control of the cotton bollworm or the tobacco budworm. This nucleopolyhedrosis virus also provides control of Heliothis spp. on corn, sorghum, tobacco and lettuce. Based on current estimates of insecticide usage this microbial could be used for 1-3 million acre-applications/season on cotton. If the virus, which is now registered, proves as effective as current insecticides its use could extrapolate to a replacement of over 4 million pounds of chemical insecticides/year.

The development and use of microbial insecticides is a relatively new field for both Government agencies and industry. The financial investment required for an industry to develop a microbial insecticide, although perhaps not as large as for a chemical insecticide, is still high (estimate $2-5 million); however, risks are greater in this unknown field and patent protection is limited. Thus, industry is reluctant to carry out the research necessary to develop microbial insecticides, although it is willing to exploit them once ARS scientists have undertaken the preliminary research and demonstrated a reasonable degree of

assurance that a particular agent is effective against target insects and can be produced at a cost that would allow its practical use. Once this has been done, industry is willing to perform the necessary research and development to carry the product to commercialization. A considerable incentive to industry is the known safety of these agents. These entomopathogens are generally regarded as safe, and residues left on food and fiber are considered harmless. Since they are normally present in nature, they are not considered to contaminate the environment in any way.

a Bacteria

i *Bacillus thuringiensis*. The present usage of BT is sometimes limited by cost -- formulations of the δ-endotoxin cost the user about $9.25/pound, and the usual application rate is between 1/2 and 1 pound/acre. In other cases, the toxin is not active enough to effectively control the pest -- at least at a cost low enough to be practical. Sometimes usage is borderline or restricted by effectiveness or cost from certain types of application. For example, BT formulations now available are effective against the gypsy moth, the spruce budworm, and the tussock moth when applied by ground equipment. However, so far they have been less effective when applied by air, a defect that has restricted their use in forest-wide applications.

There is one characteristic of the δ-endotoxin that is particularly important to note: the δ-endotoxin produced by one isolate of BT may kill different species of insects than the δ-endotoxin produced by another isolate, or at least it may have a different degree of activity against a particular insect species. The types of insects a toxin kills and the degrees of activity it has against them make up the "spectrum of activity" of that toxin. All present commercial formulations are based on the HD 1 formulation, prepared from an isolate and production procedure developed by Agricultural Research Service scientists, and thus have the same spectra of activity. However, new formulations may differ. Serological techniques should be helpful in identification of new formulations of δ-endotoxin.

Some isolates of BT produce a second toxin, completely unrelated to the δ-endotoxin. This toxin, called the β-exotoxin, is more of a general poison, being toxic to many different insects, but particularly to flies, and has sufficient mammalian toxicity to warrant caution in its use. Still other isolates produce what appear to be still other unrelated toxins which can also kill insects, but these have not yet been characterized. Here also, serological methods can provide highly specific means for characterization of the various toxins. With this background in mind, the following are the current technologies on those crops or insects on which the use of BT is current or is being developed:

(a) BT in the control of the cabbage looper. The main pesticides used for control of the cabbage looper are Lannate, Galecron (Fundal), and BT. All are relatively expensive to use since they cost about $9.25/pound and application rates are in the range of 1/2 to 1 pound/acre. The cabbage looper is a pest on many crops, but is particularly so on lettuce, cole crops, and leafy vegetables. In 1972, about

440,000 acres were devoted to these crops, with a crop value of about $500 million. An estimated 600,000 pounds of BT were applied to these crops in 1974, slightly less than 1/2 the total market of the three products for the control of the cabbage looper. Thus, roughly 1,200,000 pounds of these materials, with a retail value of over $11 million, has been estimated to be used to control this insect.

(b) BT in the control of Heliothis species. BT is quite active against the tobacco budworm and the corn earworm or bollworm. About 20% of the 200,000 acres of tobacco treated for the tobacco budworm are treated with BT. Application costs are competitive with Lannate, Azodrin, and Orthene, the commonly used chemicals. However, BT only protects cotton at uneconomical and impractical rates, and is not used on this crop at the present time. Effective control of Heliothis on cotton will need either a more active toxin, improvement in the application method (possibly incorporation of a bait) or both. Since the potential market is large (approximately 3,500,000 acres of cotton were treated three times for control of Heliothis in 1972), and the need is great (Heliothis spp., particularly tobacco budworm, are becoming resistant to chemicals), development of a successful BT would be extremely valuable. A study of the ecological distribution of BT would provide needed data on the presence of this bacterium in nature.

(c) BT in the control of the European corn borer. The average annual loss to this pest is 3.5% (ARS Agric. Handbook 291, p. 42, 1965) of the total crop. In 1975 this amounted to about $560,000,000. About 10,000,000 acres of corn are treated three times each year to control the European corn borer with Sevin, Furadan, Thimet or EPN. BT is not presently used on corn but would be suitable for the treatment of at least 1,000,000 acres of hybrid seed corn each year. Wider use will depend on the development of formulations that also control corn earworms.

(d) BT in the control of stored-product insects on grains and peanuts. The two principal pests of wheat, corn, grain, sorghum, rough rice, and peanuts are the Indian meal moth and the almond moth which destroy about 3% of a crop worth over $10 billion. About 25% of these products are treated to control these two insects, using malathion, synergized pyrethrins, dichlorvos PVC, or fumigation. None of them work well; the insects are becoming resistant to malathion and the pyrethrins; dichlorvos PVC works only on adults and then only in airtight bins (a rarity on farms); fumigation is dangerous, expensive, and the control is short-lived. BT is not yet registered for use on these insects, but tests with current formulations show that BT can control these insects at an economical rate.

The Indian meal moth is also a pest of stored raisins, prunes, almonds, and walnuts. Malathion is used here, but the moth is becoming resistant to this treatment. BT could possibly work here, but has not yet been evaluated. A granulosis virus attacks this insect, and this is being studied as a possible control tool, but work is still preliminary.

(e) BT in the control of Spodoptera species. Three of the species of Spodoptera that are pests in the U.S. are the southern armyworm, the beet armyworm, and the fall armyworm. These are

pests on a wide variety of crops, and it is difficult to find any accurate figure as to the amount of chemicals used to treat the insects or the amount of acreage involved. There is also a species of Spodoptera, S. litura, (the cottonworm) that is of major importance in the Far- and Middle-East and in the Mediterranean area, although it is not found in the U.S. Present BT formulations are not active against any of these species of Spodoptera. It is known, however, that some isolates of BT produce a toxin or toxins that kill the armyworms, but not the cottonworm, while still other isolates produce material toxic to the cottonworm.

(f) BT in the control of flies on cattle in feed lots and in dairies. The present methods of controlling horn flies, stable flies, and face flies on cattle in feed lots and dairies require considerable handling of the animals, with a high labor cost, and must be repeated 8-10 times/year. The present chemicals used, methoxychlor or a toxaphene-dichlorvos mixture, pose residue problems. Also, flies appear to be developing resistance to them. While the BT δ-endotoxin is not active against flies, a second toxin produced by BT, the β-exotoxin, is very toxic to these insects. The β-exotoxin can pass through the digestive tract of an animal and end up intact in the feces, where it can prevent the development of fly larvae that breed in feces such as houseflies. This offers an easy way to control flies without handling the cattle, through incorporating β-exotoxin in the feed. However, this toxin is toxic to mammals as well as to flies, and it will be necessary to be very cautious in developing it for use in cattle. BT appears to produce other toxins active against flies, some of which may be related to the β-exotoxin (but which might be safer to use), and some of which appear to be unrelated either to the β-exotoxin or to the δ-endotoxin.

(g) BT in the control of mosquitoes. Adult mosquitoes are presently controlled by malathion, Dibrom, and sometimes Baytex. Costs per acre depend on type of application. Ultra-low-volume sprays average 25-30 cents/acre when applied by air and 15-18 cents/acre from the ground. Conventional low-volume applications cost about $1.50/ acre by air and 50 cents/acre from the ground. Larvae of mosquitoes are commonly attacked by insect growth regulators, costing $2.50-2.75/acre when applied by air. There is some evidence that the δ-endotoxin produced by some isolates of BT may also be active against mosquito larvae, but more research is required to tell if they will be practical to use.

(h) BT in the control of forest insects. While control of forest insects is the responsibility of the Forest Service, rather than the Agricultural Research Service, the procedures that are used to develop improved formulations of the δ-endotoxin for use in crop protection can also result in better BT's for the control of forest insects. Three major pests of the northern forests -- the gypsy moth in the Northeast, the spruce budworm, and the Douglas fir tussock moth in the Northwest, are susceptible to the δ-endotoxin. Tent caterpillars and webworms, general throughout the country, are very susceptible to the toxin. While the tent caterpillars, webworms, and tussock moths can be controlled with chemicals, those used against the spruce budworm and the gypsy moth have some drawbacks. BT is extremely effective against these insects when applied with ground equipment, but is less

effective against the gypsy moth, spruce budworm, and the tussock moth when applied by air. To achieve good control of these insects with aerial application, it may be necessary to develop more potent formulations of the BT and to devise formulations that will allow efficient dispersal and penetration of forest canopies -- since the leaves in the upper parts of the trees help to protect the pest insects.

(i) Bacillus sphaericus in the control of mosquito larvae. At the present time, mosquitoes are controlled only by the use of various chemical insecticides. Malathion, Dibrom, and DDT (where permitted) are used against the adults, and oils or insect growth regulators against the larvae. ARS and State University scientists have studied Bacillus sphaericus, a bacterium that produces a toxin that kills mosquito larvae. There are indications that the bacterium may multiply and persist in an aquatic environment and control mosquito larvae. B. sphaericus can be produced in large quantities, and pilot-plant-sized quantities have been formulated for dispersal in various field trials to evaluate the practical potential of this microbe.

(j) Bacillus popilliae in the control of the Japanese beetle. B. popilliae has been produced in this country since 1948 by State and Federal laboratories and more recently by industry. Production is difficult. The bacteria reproduces only by injection into the Japanese beetle grub where they multiply. After the disease is fully developed, the grubs are ground, dried, and formulated into a usable product. Obviously, such a product is limited in annual production (currently about 26-60,000 pounds/year). Since the Japanese beetle is a pest in more than 14 States, this is not an adequate amount. Although the bacterium can be grown free of the living insect, it will not form infective spores under these conditions. ARS scientists have been working for 16 years to develop a suitable fermentation for production of infective spores without success. They were able to get spores produced in about 20% of the cells, but these were not infective. Recently, other ARS scientists have found that the bacterium does not form a normal nucleic acid when grown in artificial medium. This could possibly account for the failure of the organism to form infective spores. This is being investigated. Vegetative rods can be grown readily in artificial media but, while they are infective, they die easily. The possibility of encapsulating these living rods and distributing them on beetle-infected turf to attack the young grubs is also being investigated.

b Fungi

Fungi were among the first pathogens of insects to be considered as agents for microbial control. Fungal species with both wide and narrow spectrum insect host range are available to meet specific pest problems. The experimental technology for production and development is relatively well developed. Most insect fungal pathogens grow well in artificial media and conventional equipment can be used for application. Storage is a serious problem with fungi; formulation is vitally important for some applications but has been little studied. The mode of disease

induction and development is poorly understood in many cases.

Production of fungi appears economically feasible since existing technology and equipment may be utilized in many cases. The market potential for fungi is not known, but since major pests are susceptible, it is undoubtedly adequate to encourage development. A wide variety of fungi have been tested against various types of insects inspired by observations of impressive numbers of insects destroyed in natural epizootics. Some examples of significant levels of infection include:

i *Coelomomyces* spp. used against *Anopheles* and *Aedes* mosquito larvae has shown promise for control.

ii *Entomophthora* spp. have been used with success against the brown tailed moth and green peach aphid.

iii *Beauveria bassiana* is now produced in the USSR for use against a number of important agricultural pests but only in conjunction with sublethal doses of chemical insecticides. In the U.S. *Beauveria tenella* has shown promise as a mosquito control agent.

iv *Metarrhyzium anisopliae* has caused high mortality in wireworms and on the European cornborer; some isolates are very pathogenic for virtually all mosquito larvae.

v *Nomuraea* (*Spicaria*) *rileyi* induces natural epizootics in some major pests such as the beet armyworm, green cloverworm, tobacco budworm, corn earworm, and others. Early season artificial dissemination of the fungus has been used to effect control of large late season populations of caterpillars.

vi *Aschersonia* spp. has been reported as an effective control agent of whiteflies in the U.S. Development of these fungi for microbial control is underway in the USSR.

vii *Hirsutella thompsoni* is primarily a pathogen of the citrus rust mite in Florida and is a candidate for development as an acaricide in citrus. It also attacks some spider mites, and bud mites.

Some fungi produce substances toxic to insects. At least 22 insecticidal toxins, produced by 17 different fungi, are known. Unfortunately, most of these toxins have not been characterized, and most have been tested against insects only by injection -- a method not suitable for evaluating field effectiveness, where insecticides must be able to affect the insect either by being eaten or by being absorbed through the skin.

c Actinomycetes

The actinomycetes are a very common group of microorganisms, widely distributed in soil and water. They are unusually versatile and diverse in their physiology, as demonstrated by the wide variety of chemical structures to be found among the antibiotics they produce. They are known to produce many different types of physiologically

active substances, including antibiotics active against bacteria, fungi, protozoa, nematodes, and cancerous cells. They are used in the production of steroids. Some produce substances that appear to have plant growth-stimulating effects, and there are others that seem to produce materials that inhibit the growth of some plants. Most of these active substances are toxic, but many are not, and the actinomycetes are considered the most valuable of all microorganisms as potential sources of useful compounds.

In spite of the reputation of the actinomycetes, very little has been done to screen them as sources of microbial insecticides. However, preliminary studies have shown that actinomycetes do produce insecticidal substances. Preliminary investigations by ARS scientists indicate that a routine screening of actinomycetes would turn up many such agents. The few actinomycete insecticides that have been studied (mostly by Japanese workers) have been toxic to mammals, but, in two cases reported, where an actinomycete produced pairs of chemically-related insecticidal products, insecticidal toxicity and mammalian toxicity did not coincide, offering the real hope that safe antinomycete-derived insecticides can be found. What little is known about these agents indicates that, depending on the actinomycete used to produce them, they can kill a wide variety of pest insects.

d Protozoa

i *Nosema locustae* in the control of grasshoppers.

While grasshoppers are a serious pest on rangelands of the Western U.S., some grasshoppers can be tolerated -- up to 8 grasshoppers/square rod. Treatment of rangeland is generally begun when the grasshopper population reaches a density of 18-20 grasshoppers/square yard. Since rangeland production is only valued at $5/acre, treatment costs must be minimized -- even annual treatment with the currently used chemicals (malathion and carbaryl) is too high, even when application costs run about $1/acre. For this and other reasons, probably less than 1/10 of the acreage infested with economically important densities of grasshoppers is treated. There are large control programs conducted under a cost-sharing arrangement between the Federal Government, State Government, and the landowner: In 1975 for example, 650,000 acres were treated under these programs.

Nosema locustae causes a natural disease of grasshoppers that offers an opportunity to reduce populations of the grasshoppers to sub-economic levels. Small-plot test studies have established that treatments of 1 million spores of *N. locustae* per acre will cause a 50% reduction in the density of grasshoppers, a reduction that may be sufficient to obtain effective control. Furthermore, about 30-50% of the survivors will harbor the disease and lay fewer eggs, many of which will not be fertile. Those eggs that do hatch will produce diseased insects which can carry the spread of the *Nosema* on to succeeding generations. Pilot-scale tests indicate that the spores could be produced cheaply and the cost of use of *Nosema* would be less than the cost of chemicals. A large-scale field test is underway in which 16,000 acres of rangeland were treated with *N. locustae* and compared with rangeland treated conventionally and with other land left untreated as a control. Preliminary results are very encouraging, but no final conclusions can be drawn until the experiment is completed 3 years from now.

ii Nosema algeriae. Another microsporida, Nosema algeriae, is an excellent pathogen of mosquitoes of the genus Anopheles, the carrier of malaria. Preliminary tests are promising and indicate that treatment of breeding areas with this protozoan could greatly reduce the incidence of malaria, since this human parasite does not complete development in the mosquito adult before it is killed by the protozoan.

iii Nosema pyrausta. This pathogen shows possibilities for control of European cornborers. A water suspension of spores sprayed on corn plants reduced the number of larvae per plant by 48%.

iv Mattesia trogodermae. This protozoan shows promise for control of carpet beetles in stored products. The effects of dispersion of spores by adults via pheromone-baited inoculation sites resulted in an average mortality of 85% in their progeny when adult density was high (16 pairs/in.^{2}); low density (1 pair/in.^{2}) resulted in 36% mortality.

e Viruses

Viruses can cause diseases in insects and offer a means for insect control. Insect viruses are quite common; for example, there are at least 80 nuclear polyhedrosis viruses and granulosis viruses that have already been isolated and that are known to infect major insect pests. Present evidence indicates they are not harmful to beneficial insects, to plants, to animals, or to man. The viruses offer tremendous potential for insect control, but few have yet been studied extensively. The following sections list some of these viruses, the insects that they infect, and the current status of research on them. However, first, it would be useful to define these viruses and to discuss the principles of their production: The principal viruses being studied belong to a group of "occluded viruses" called the Baculoviruses. These can be divided into two groups: the nuclear polyhedrosis viruses (NPV), which can be further subdivided according to their distribution in the protein packet that holds them: (a) the single embedded viruses (SEV), which are usually highly specific for one species of insect and may not grow well or at all in homologous tissue cell lines, and (b) the multiple embedded viruses (MEV) which often kill many different insect species and grow well in various tissue cell lines; and a second group, the granulosis viruses (GV), which are highly specific for one insect species and do not grow outside the host even in homologous insect cell lines.

At present, viruses must be produced in living insects. Thus, the production of viruses requires the development of mass-rearing techniques for raising host insects. Some insects are easy to rear; others are difficult either because of some specialized needs, or because they are very cannibalistic and must be reared in separate containers, increasing rearing costs. Many of the rearing procedures have been developed for other programs and can be easily modified for use in the production of viruses. Viruses are produced by infecting developing susceptible larvae at a suitable age and then later harvesting the virus from the diseased larvae. Recovery of the virus is generally an easy and inexpensive operation, but rearing of the insects can be costly, and further efforts

are needed to simplify and make less expensive the production of the insect. If inexpensive ways of growing insect cells in tissue culture can be found, this method could replace the living insect as a production tool for these viruses.

Viruses differ in their infectivity. Some are very virulent and kill the infected insect rapidly; others may only cause a chronic disease which reduces the reproductive potential of the insect or only kill after a prolonged period. Thus, the selection of individual viruses as control agents requires a knowledge of their action to be sure they have potential in insect control.

i Heliothis virus. The *Heliothis* virus is so called because it is a nuclear polyhedrosis virus that infects several species of *Heliothis*, but no other kinds of insects. It has been studied for several years, particularly against *Heliothis* on cotton. Results at first were not encouraging; mostly, apparently because the early formulations were not satisfactory. One of the primary problems has been the short life the virus has in the field, particularly when applied on cotton. Much progress has been made in improving the stability of the virus, and prospects for obtaining effective control of *Heliothis* on cotton appear brighter now.

The *Heliothis* virus was the first virus to be developed for commercial use. Since *Heliothis* species are cannibalistic, rearing of the insect is difficult, complicating the production of the virus. Much progress has been made. This virus was the first one for which a registration and label from the regulatory agencies was sought, and it required the cooperation of ARS, EPA, and industry to develop guidelines for evaluation of its safety and efficacy. The virus has received an Exemption from the Requirements of Tolerance, indicating that the EPA is satisfied of its safety. The guidelines developed for this virus will help in the collection of safety and efficacy data on other virus materials when attempts are made to register them.

ii Cabbage looper virus. The nuclear polyhedrosis virus that infects the cabbage looper commonly causes massive epizootics that decimate populations of the looper. Farmers frequently make use of this fact to help control the looper. When they find diseased insects in their fields, they grind them in water and spray the suspension on fields where the disease has not yet appeared. Since this virus affects no other insect, the market is limited, and little effort has been made to develop commercial formulations. However, virus control of the cabbage looper could have considerable value for control on lettuce and cabbage crops, perhaps in conjunction with formulations of the *B. thuringiensis* δ-endotoxin, and some research with this virus is continuing.

iii Alfalfa looper virus. ARS scientists first found this virus in diseased alfalfa loopers. This virus is of the single-embedded type and is infective to a wide range of pest insects, including the cabbage looper, the beet armyworm, the diamond-backed moth, the cotton leafperforator, the saltmarsh caterpillar, the tobacco budworm,

the European corn borer, and, of course, the alfalfa looper. Less susceptible pests include the bollworm and the fall armyworm. The list of susceptible pests is likely not complete. At present, countrywide tests of this virus are being carried out to evaluate its control of insects on cabbage, soybeans, and cotton. First results have been promising. Basic safety tests have been done and demonstrate that this virus is harmless to other living animals and plants. A petition to the EPA to obtain a Temporary Exemption from the Requirement for Tolerance and a Special Permit for testing large acreage is being prepared.

Alfalfa looper virus can be produced in the cabbage looper, an easy insect to rear, so that the cost of production should be relatively low. This would be particularly important if this virus should prove to control Heliothis species, since production of alfalfa looper virus would be cheaper than that for Heliothis virus, which must be produced in cannibalistic insects.

iv Alfalfa caterpillar virus. The alfalfa caterpillar is a very serious pest, particularly in California, where alfalfa is almost continuously harvested. In 1974, the yield loss was $2,902,440 and control costs were $1,521,367 (Calif. Dept. Food/Agric., E-82-14, Sacramento, CA 1975. 14 p.). Steinhaus and Thompson proved the efficacy of this virus in the field, and, as a result, the University of California has for years recommended that farmers collect virus-killed insects, crush their bodies into the spray tank, and control the insects on alfalfa with this homemade virus. This is not desirable for a number of reasons, one of which is safety. The virus could be of considerable value and should be developed along the lines of the alfalfa looper virus and cleared with EPA as a registered product.

v Granulosis virus of Indian meal moth. The Indian meal moth is a major pest of stored agricultural products. It has previously been discussed in the section of B. thuringiensis as a major pest in stored grains and peanuts. It is also a major pest in stored nuts, such as almonds and walnuts, and in dried fruits, such as raisins and prunes. These are major products, with an annual value in excess of $300 million.

Treatment in the case of nuts and fruits is usually by fumigation, followed by malathion. Probably close to 3/4 of the crop is treated. However, the insects are building a resistance to these treatments. There is a granulosis virus that is very infectious to the Indian meal moth, and ARS scientists are studying the use of this virus in the treatment of the Indian meal moth on nuts and fruits. The present method is to lightly spray the nuts or the fruits as they pass on a conveyor belt, spraying at the rate of 2.5×10^6 capsules (the infective unit of the granulosis viruses) in 2 ml water/100 gram product. Preliminary results are very encouraging.

3 Weed biotic agents except pathogens. Augmentation, manipulation, and conservation of organisms already occurring within the U.S. to effect greater control of weeds is a relatively new and untried area of research, compared with the introduction of foreign organisms, although the method has been used in several instances to

control insect pests. Research is needed to develop new methods of augmentation, manipulation, and conservation and on how to apply them to problem weeds to achieve the most efficient control systems. Lack of adequate rearing facilities, quarantine, and overseas laboratories to search for promising suppressants prevents full exploitation of the potential of biological control work within the U.S.

a Augmentation. Direct methods to increase populations of suppressant organisms are probably the most obvious to apply. Leaf beetles to control St. Johnswort in California were distributed from areas of surplus to increase control in other areas. In California, the method was used only to increase the rapidity of spread from the areas of original release. However, the method could also be used on a continuing basis to distribute suppressants into climatic areas where they are not able to become permanently established or where they are needed earlier or later in the season than they occur naturally. Insects to control cactus are used in this manner in Australia where they are systematically distributed each year from Queensland to New South Wales where the cooler climate does not naturally permit control. A few species have been cultured on artificial diet for distribution in the field; for example, cerambycid beetles were released to control lantana in Australia, and the nutsedge moth was reared and released experimentally in Mississippi to control purple nutsedge.

Recollecting natural enemies from naturally occurring field colonies avoids the expense of artificial culture. Periodic release also favors adaptation and establishment of the natural enemies in formerly unsuited habitats.

It is usually assumed that suppressants already present are, a priori, less effective than desired, otherwise the weed would not be considered a problem. Therefore, the classical method of introducing foreign organisms to control weeds usually appears more promising, especially if the weed itself is of foreign origin. However, in the case of many native and some introduced weeds, it is felt that the indigenous suppressants are having some impact. How effective are these suppressants and can their action be augmented? In some instances the augmentation approach may have certain advantages over the introduction of exotic natural enemies.

For example, suppressants of foreign origin that are safe for introduction and that give sufficient control may not be found or may not exist, or foreign introduced organisms might give control in all areas whereas control is desired only in certain areas, as in the case of weeds that also have some beneficial value. Augmentation has the advantage of the "turn on-turn off" feature of chemical controls in that it can be applied only in designated areas or times.

Augmentation techniques on the other hand often have the disadvantage of requiring a constant input of resources to maintain populations of the natural enemies at higher levels than exist under natural conditions. It is assumed that suppressant populations will fall to the previous natural level when the energy input is withdrawn. However, certain conservation techniques may not require an energy input or may even result in an energy saving.

Two obstacles to control of weeds by augmentation are a poor understanding of how natural enemies affect weed abundance and, secondly, the high cost of producing populations of suppressants large enough to give control. Research is needed on the basic biology and ecology of weeds and suppressants, and their interactions. Research is also needed in the development of cheap methods of mass producing suppressants or of otherwise increasing their numbers in the field. Of particular importance in augmentation is the need to develop techniques of analyzing the damage caused by the weed, the potential cost of various control procedures, and whether a given procedure will be economical to apply or will result in a saving over current control methods.

b Manipulation. Modifications of the agroecosystem have been used in several instances to obtain increased control from suppressants. In Australia and South Africa, where the mature growth of cactus plants was not attacked by natural enemies, the plants were felled, after which the suppressants attacked and increased to high numbers on the seedlings and new growth, eventually killing the plants. Suppressant populations were also increased in the field by reducing their natural enemies; for example, mealybug (Dactylopius) populations increased greatly and gave control of cactus in Africa when predatory ladybird beetles were killed with DDT.

Increasing the competition from other vegetation is often important in increasing the amount of control that suppressants provide; theoretically, by manipulating the competing vegetation, control can be improved. Competing grasses have been used in California to displace aquatic weeds growing in irrigation canals.

In South Carolina, where cold winters hinder buildup of large spring populations of the alligatorweed flea beetle, the plant growth was altered by spring applications of 2,4-D (which does not directly harm the beetle). This slowed the plant growth permitting the beetle to increase in number and eventually to control the plant later in the season.

Fertilization or the use of chemicals may increase acceptability or nutrition, favoring the suppressant. For example, numbers of a moth (Cactoblastis) increased 5-15 times and controlled pricklypear when the plants were fertilized, whereas those growing on poor soil were not controlled.

c Conservation. Conservation measures have been little used in biological control of weeds, but several methods used in biological control of insects might be applied. Possible examples are timing of insecticide applications on the crop to conserve insect populations attacking weeds, providing alternate host plants or food plants for suppressants along field margins or in strips in the field, introducing parasites to control specific natural enemies of weed feeding insects, or modification of planting dates, crop rotations, cultivation, etc., to favor weed feeding insects. These methods require a thorough understanding of the ecological relationships of the agroecosystem and of the suppressants.

Research is needed in the basic biology and ecology of each weed-suppressant ecosystem to make the most appropriate selection of candidate weeds for control efforts and to determine the most efficient method of control to use. Also, basic ecological research is needed to identify the key factors regulating populations of suppressants and weeds and to find weak points in the present natural control systems. Research is also needed in developing predictive models of the effects that various control measures will have on weed populations.

4 Weed pathogens. Endemic weed pathogens offer unusual opportunity for control of weeds because they already occur naturally in the U.S., therefore, they are not restricted to research under quarantine and containment. These pathogens can be mass produced and released into crop environments in pilot research programs in the U.S.

An endemic fungal pathogen, Colletotrichum gloeosporioides f. sp. aeschynomene kills northern jointvetch, (Aeschynomene virginica), a severe leguminous weed of rice. A new concept of biological control of weeds has been developed with the discovery of this fungus of northern jointvetch. This new approach of biological weed control involves the dispersal of a bioagent in the same manner as chemical agents are applied to fields. Rice fields, infested with northern jointvetch, are inoculated with spores by aerial dispersal of spore-water suspensions. A team of scientists with ARS, the University of Arkansas, and private industry is pilot testing the feasibility of using this endemic pathogen for control of northern jointvetch in rice. Under this pilot project the pathogen has been researched--life cycles, culture, growth requirements, specificity, and field efficacy. An experimental use permit and a temporary exemption of residue tolerance, granted by EPA to the University of Arkansas, permitted field testing the fungus in 1975. Continued pilot testing will be conducted in 1976 and 1977 if EPA extends the experimental use permit and exemption of residue tolerance. The major deterrents to registration for use in rice are: (1) the requirements for EPA registration are unknown, (2) only a small market is available, (3) the concept is covered by a U.S. Government patent.

Research indicates that the disease controls northern jointvetch in commercial rice fields. Because fresh spores lose their viability a few days after completion of fermentation, research is required to develop methodology of processing and storing spores for a commercially acceptable, effective product. Also, considerable toxicological data must be developed before the product can be registered with EPA for commercial use.

Several other endemic pathogens including Cercospora rodmanii of water-hyacinth (Eichornia crassipes), Phytophthora citrophthora of strangler vine (milkweed vine) (Morrenia odorata), Colletotrichum malvarium of prickly sida (Sida spinosa) are promising for weed control, but only limited research has been conducted.

Surveys for and identification of potential fungal pathogens for bio-control are greatly simplified by systematic collection and cataloging of fungi as in the USDA-ARS National Fungus Collection and other great fungal collections of the world. Presently, the information from these collections is scattered among several publications such as Host Index

of Plant Diseases (USDA Agr. Handbk. 165); Index of Fungi, published by the Commonwealth Mycological Institute; Saccardo's Sylloge Fungorum and Oudeman's Enumeratio Systematica Fungorum. These are great reservoirs of information that provide what is known of host range of pathogens, taxonomic relationships, behavior of pathogens and their geographic distribution.

5 Antagonists of plant pathogens. The term antagonism includes the whole array of biological interactions which control plant pathogens including inhibition or destruction of one organism by a metabolic product of another, competition, and parasitism or predation. There are many examples of biological control of plant pathogens already in effect, most of which were developed empirically as part of cultural control methods. Some specific developments are as follows:

a Selective soil treatments have been developed that weaken pathogenic propagules or predispose them to decay by soil organisms (e.g., control of *Armillaria* root rot of apple in California with carbon disulfide which permits biocontrol by *Trichodemora*).

b Organic amendments are used to initiate microbial production of metabolites or other microbial activity that starves propagules (e.g., control of bean root rot by barley straw), or causes decay or other reduction in propagule numbers (e.g., control of phymototrichum root rot of cotton).

c The discovery of highly antagonistic and protective floras that are genetically controlled by the host in some cases ("resistance" in certain wheats to common root rot), induced by past cropping systems (takeall decline phenomenon initiated by continuous wheat), or by aerially applied rapidly translocated chemicals (streptomycin, urea) in other cases, on root surfaces or in infection counts ("resistance" in monocots to phymototrichum root rot).

d The use of avirulent (non-pathogenic), hypovirulent (low pathogenicity) organisms related to target pathogens that can be applied in advance of the pathogen to stimulate resistance in the host to the pathogen (developed for control of certain vascular wilts in particular, but also for control of chestnut blight; not yet in commercial use because of risks involved in starting a new disease, and also because of lack of technology for handling the candidate organisms).

e The use of bacteria with bacteriocins (antibiotics) effective against bacterial plant pathogens (in commercial use in Australia to control crown gall of fruit trees).

f The use of residue management practices that encourage replacement of pathogens in host tissue by saprophytes (stubble mulching of wheat to encourage saprophytic take-over of the straw and to reduce *Fusarium* buildup).

g The use of hyperparasites or other antagonists that suppress inoculum production of pathogens (Tuberculina maxima kills white pine blister rust fungus in cankers and reduces inoculum production in the Pacific Northwest).

h The use of antagonistic microorganisms for seed dressings to protect seedlings against pre- or post-emergence seedling blights (protective bacteria and fungi have been identified as seed dressings that equal fungicides in protection of corn against damping off, but not yet in use because of difficulties in commercialization).

i The use of cultural practices such as irrigation for control of potato scab, ammonium nitrogen for control of take-all, or deep chiseling for Fusarium root rot, all of which operate to control the pathogen through biological means.

j Fomes annosus root rot of conifers is now controllable commercially by stump application of Peniophora gigantea which takes possession of the stump and blocks infection by F. annosus. In Australia, Fusarium lateritium applied to pruned branch stubs of apricot trees protects against Eutypa canker and stem die-back.

In addition to the above examples, there has been much information gained about the ability of many different bacteria, actinomycetes and fungi to suppress or parasitize plant pathogenic fungi in vitro and in model experiments in soil. However, the use of these antagonists as introduced organisms to control soilborne plant pathogens has not yet been possible because the ecological complexities of soil as a habitat for microorganisms make the establishment of an alien organism in soil difficult, and thus has hampered development of control methods that consistently work. Despite this, successful control of a limited number of pathogens under specialized conditions has been achieved. The dissemination of biological control agents in pellets in field tests for controlling peanut diseases has been obtained. Successful control of slash pine seedling disease by biological means in nursery soils has also been obtained. Moreover, the successful commercial use of nitrogen-fixing Rhizobium introduced with legume seeds gives encouragement that microorganisms can be introduced into soil if the proper conditions prevail or are provided.

B Visualized Technology

1 Parasites and predators.

a Minimization of the effects of pesticides on natural enemies in all areas where insecticides are used, or potentially could be used on a large scale such as cotton, soybeans, vegetables, fruit, and corn (5 years).

b Utilization of plant varieties resistant to pest populations, but having minimal impact on natural enemy populations with particular emphasis on crops such as cotton, soybeans, wheat, corn, and grain sorghum (5 years).

c Mass production and distribution of natural enemies such as Trichogramma sp., Microplitis croceipes, Reesimermis nielseni, Opius spp., Lixophaga diatraeae, Jalysus spinosus, Brachymeria intermedia, Pediobius foveolatus, and Amitus hesperidum for use in augmentation programs for control of pests such as Heliothis spp., pink bollworms, mosquitoes, fruit flies, Spodoptera spp., sugarcane borer, plant bugs, tomato hornworms, tobacco budworms, cabbage loopers, gypsy moth, Mexican bean beetles, and citrus blackflies thereby increasing their effectiveness by 50% (10 years).

d Mass production of Trichogramma spp., hymenopterous and tachinid larval parasites, and a parasitic nematode on an artificial diet thereby reducing entomophage production costs by 50% or more (10 years).

e Utilization of methods for measuring and maintaining the quality of laboratory reared beneficials listed in (c) (5 years).

f Replacement of the host, pollen, or honeydew that retains, arrests, and/or sustains predator/parasite populations in crops such as cotton, tobacco, soybeans, citrus, and vegetables with economical artificial foods (7 years).

g Utilization of behavioral chemicals to obtain maximum efficiency of parasites and predators such as those listed in (c) when used with natural and/or released beneficials.

h Alteration of agroecosystems involving crops such as cotton, tobacco, soybeans, sugarcane, grain sorghum, wheat, and corn to the advantage of biological agents so as to make them 50% more effective.

i Reduction of the effort and funds required to test host-parasite or predator-prey interaction by the use of computer simulations (5 years).

2 Insect pathogens. Successful development of microbial insect control agents will depend on two principal factors: (1) development of effective agents and (2) public acceptance of their use. Fortunately, the registration and commercialization of the B. thuringiensis-δ-endotoxin and the registration of the Heliothis virus have demonstrated that the EPA will register microbial insecticides, and can be convinced that they are safe and effective. Sales of the δ-endotoxin, which have reached a level of 200,000 pounds/year demonstrate that, if the agent is effective, the public will buy it. Thus, these two problem areas which could be of serious concern in planning the future of microbial insect control agents, seem to be resolved. This does not mean, of course, that each future agent, as it is developed, will not have to be proven safe and effective, but it does mean that once it has satisfied these criteria, it will be used.

a Bacteria. Bacillus thuringiensis. It is known that the endotoxin produced by one isolate of B. thuringiensis may not kill the same kinds of insects as the δ-endotoxin from another isolate -- or at least that the degree of effectiveness of the toxins against different insects may not be the same. In addition, of course, B. thuringiensis produces other toxins -- the β-exotoxin and other uncharacterized insecticidal substances. Thus, the toxins produced by individual isolates of B. thuringiensis may differ, and finding a culture of B. thuringiensis better for the control of one kind of insect may or may not lead to better control of a second kind of insect. Nevertheless, the search for improved formulations of B. thuringiensis for use in any area of insect control requires the same basic fermentation studies, starting with the screening of hundreds of isolates of the bacillus. Thus, the most efficient way of conducting this screening is for one laboratory to grow each culture in sufficient quantities so that many different scientists can test the formulation it produces. Each scientist can then select those cultures that appear to be the most promising in relation to his particular area of interest and study them in more detail. This is, in fact, being done, with scientists at several locations and interested in a wide variety of insects, all testing formulations produced by a single laboratory. Since more than one scientist may be interested in a particular isolate, and since the original laboratory can help in further fermentation studies, this cooperation may in many cases, persist through a good deal of the developmental work. Thus, while the following sections discuss particular areas of research to develop practical uses for BT, it should be remembered that there may be considerable overlap between them. At this point in time, it is impossible to tell where this overlap will occur, or how great it will be.

i BT in the control of the cabbage looper. The cost of using BT for control of the cabbage looper and related insects should be reduced by 50% in 5 years. The estimated retail cost of the BT used in control of these insects in 1974 was about $5-1/2 million. Thus, even if the reduction in cost of BT failed to increase the sales for cabbage looper control, annual savings would be $2-3/4 million. It should be noted that $11 million were spent in total for cabbage looper control including chemical treatments, and it would be expected that the reduction in cost of BT would increase its share of this market. However, BT can never totally replace chemicals, since other insects sensitive to the chemicals, but not to BT, are sometimes present on the plants.

ii BT in the control of Heliothis species. The potency and efficiency of formulations of the δ-endotoxin should be increased sufficiently in 5 years, so that Heliothis can be controlled on cotton at an economical rate by this material. By the end of the 5-year period, about 3% of the control of Heliothis on cotton should be carried out using BT, at a cost of about $4.00/treatment. Further improvements should be made during the following 5 years so that at the end of 10 years, 30% of the control of Heliothis should be by the toxin. Costs of applications of the BT may not decrease, but demand should increase as Heliothis develops increased resistance to chemical insecticides. Assuming that 3,500,000 acres are treated three times (assuming 1972 to be a typical year), then it can be estimated that annual retail sales of BT for use on cotton will reach $4 million in 5 years and exceed $16 million in 10 years.

iii BT in the control of the European corn borer. Present formulations of BT show promise for use on hybrid seed corn, but some improvements in the methods of application, particularly by the use of foam, are desirable. These improvements should be far enough advanced by the end of 5 years that BT will be in general use on hybrid seed corn, holding about 20% of the market -- or about 200,000 acres. Assuming 3 applications/year, retail sales on seed corn should approximate \$2-1/2 million/year. Treatment costs will average \$4 material/acre. By the end of 5 years, more potent formulations of BT will be developed, and these should be in use by the end of 10 years, reducing treatment costs by about 50% by the end of the 10-year period, for an annual savings of over \$1 million. At the same time, improvements in the effectiveness of these formulations against the corn earworm should have been developed through the laboratory stage and be undergoing field trials. If these are successful, by the end of 10 years BT should capture at least 10% of the overall market on all types of corn, or about 1 million acres, and sales should increase, even at the lower costs, to about \$6 million/year. Formulations suitable for use on snap beans and green peppers will be developed within 5 years, and these should be evaluated during the next 5-year period.

iv BT in the control of stored-products on grains and peanuts. Much of the next 5 years will be devoted to guiding the entry of BT into the market for the control of stored-product insects. The identity and the mode of action of the δ-endotoxin should be determined. It will be known if the susceptibility of almond moths and Indian meal moths is a general phenomenon, or if it varies in different parts of the country. The extent of spore contamination of processed products, and the extent of dispersal of spores into the environment and into untreated commodities will be known. The efficacy and persistence of the BT in stored-products will be established to a point where a temporary label has been granted. By the end of 10 years, BT should be in widespread use, and approximately 1 million pounds of BT should be sold every year, with a market value of about \$9 million, for use in the treatment of grains and peanuts.

v BT in the control of *Spodoptera* species. Formulations of δ-endotoxin active against *Spodoptera* species should be developed within 5 years and ready for small-scale field trials. Present indications are that, in all likelihood, one group of toxins will be developed that are active against the beet armyworm, the fall armyworm, and possibly, the southern armyworm, while another group will be developed that is active against the Egyptian cottonworm. If field tests are successful, then commercial formulations of both groups should be developed within 10 years.

vi BT in the control of flies on cattle. The safety of the use of β-exotoxin for cattle should be known within 5 years, and, if it is shown to be safe, commercial formulations could be available in 10 years. Other forms of the β-exotoxin or other toxins produced by BT should be characterized by the end of 5 years and tested for efficacy and safety after that period. Production techniques for these toxins will be developed during the next 5 years, and steps will be taken towards accumulating safety and efficacy data, with a goal of achieving registration by the end of 10 years.

vii BT in the control of mosquitoes. During the next 5 years, the use of δ-endotoxins for the control of mosquito larvae will be explored, and promising strains of *B. thuringiensis* will be selected for further study. The fermentations of the best of these will be developed so that the toxins can be produced in large enough scale for their evaluation in field situations. During the same period, efforts will be made to reduce the cost of production to a point where it will be possible to predict if these agents will be economical enough to enjoy widespread use. If results of the 5-year study warrant it, then efforts will be made during the following 5-year period to accumulate the safety and efficacy data necessary for registration. In this case, it would be expected that 10 years from now BT would be entering the market for mosquito control.

viii BT in the control of forest insects. Much of this work will be done by the Forest Service, with the cooperation of ARS in the discovery and development of more active strains of BT. The combined effort should produce formulations active enough that BT should enjoy considerable use in the control of the gypsy moth, the spruce budworm, and the Douglas fir tussock moth. Significant use would not be expected until near the end of this 5-year period. By the end of the next 10 years, the use of BT in forests should produce a multimillion dollar market for this product. By the end of 5 years, primarily as a result of increased acceptance of the product since the present formulations are satisfactory, BT should be in general use against the tent caterpillars and the webworms.

ix Miscellaneous use of BT. Improvements in the formulations of BT developed for use against the insects already discussed in this section should result in increased effectiveness in the control of many other insects, although it is impossible to state how great these increases will be or against which insects these increases will be effected. Nevertheless, it can be expected that the "fall-out" from these studies will result in increased use against these other insects. It would be reasonable to assume that these increased sales could approach 500,000 pounds/year with a retail value of $4-1/2 million by the end of 10 years.

In addition, exploration of the control of the black cutworm, the armyworm, and the goat biting louse should be far enough advanced by the end of 5 years so that the potential of BT toxins in this area can be accurately evaluated. If any of these miscellaneous toxins prove promising, then safety and efficacy data should be initiated with a goal of achieving registration by the end of 10 years.

x *Bacillus sphaericus* in the control of mosquito larvae. By the end of 5 years, the value of *B. sphaericus* for the practical control of mosquito larvae should be known. The type of toxin produced should be known, and some knowledge of its safety should have been accumulated. The potential for *B. sphaericus* to persist in the environment and give long-term control of mosquito larvae should be known within 5 years. If *B. sphaericus* proves to be of value, then efforts to achieve registration within 10 years should be undertaken.

b Fungi 1/

During the next 5 years examination of several of the production and utilization of fungi will have progressed to the stage that large scale tests can be contemplated. Mass production techniques for the spores of fungi, probably in submerged fermentation, will have been developed. Bioassay systems will have been devised to measure quantitatively the infectivity of spores so that different preparations can be compared. Formulations will have been prepared that will help to stabilize the fungal spores in storage and infield applications. Fungi will be characterized and the environmental impact of their widespread utilization will be known. By the end of 10 years basic safety tests necessary for registration of several fungi will have been completed and commercialization should have become a reality.

A survey of various members of the Fungi should be begun and have reached the stage where, at the end of 5 years it will be possible to determine what percentage produces insecticidal toxins. At least one fungal insecticidal toxin should have been produced in sufficient quantity for field evaluation during that 5-year period, and two more should be ready for field tests by the end of the next 5-year period. A preliminary characterization should be made to see if the fungal insecticidal toxins found are similar in chemical type to aspochracin, destruxin, or aflatoxin, or whether there is a variety of different types of insecticidal toxins produced. If a variety of toxins is found, then exploration of this field should be increased.

c Actinomycetes

Two insecticidal materials from actinomycete fermentations should be produced each year and purified enough to allow characterization of their insecticidal and mammalian toxicity. By the end of 5 years, at least 2 of these toxins should be produced in sufficient quantity for field evaluation. One actinomycete toxin should have been developed far enough and be successful enough to warrant commercialization within 10 years. Ten others should be undergoing preliminary field testing by that time, and two of these should be in more advanced stages of field testing and preliminary safety testing prior to commercialization.

d Protozoa

i *Nosema locustae* in the control of grasshoppers.

During the next 3 years, the large-scale field tests described under Current Technologies will be completed. If the pathogen looks promising in these tests, registration for general use and general availability should be achieved in 3 to 5 years. Present studies indicate that the cost of production of 1 billion spores of *N. locustae* (the amount used to treat 1 acre) will be about $0.05. At present prices, the wheat bran cost will be about $0.07/acre. Aerial application costs, using large Category A

1/ In this and in the section on actinomycetes, target insects have not been listed because, in general, these programs can be designed to attack any selected insect pest. The programs will screen unexplored areas of research, and the target insects will be selected as the programs develop.

aircraft flying swath widths of about 1,000 ft will be about $0.15/acre (based on 1975 fuel costs). Personnel costs should be about $0.05/acre. This means the total cost for producing and applying the pathogen will be between $0.30-0.35/acre.

It is expected that treatments with N. locustae should reduce densities to noneconomic levels in 50% of the infested areas, thus reducing by 1/2 the acreages requiring chemical insecticide. This goal could be expected within 5 years. Within 10 years, we could expect about 75% less use of insecticides. However, we would expect increased use of the pathogen over and above the present use of chemical insecticides. In other words, we would be using N. locustae.

ii *Nosema algeriae*. Little effort is being placed at present into the study of N. algeriae for the control of mosquitoes. It is expected that during the next 10 years, preliminary evaluation of this protozoan may have been carried out, but widespread use of this organism, even if these evaluations are encouraging, could not be expected during this 10-year period.

iii *Nosema pyrausta*. Reduce corn losses from European corn borer by 20%.

iv *Mattesia trogodermae*. Reduce losses in stored products from carpet beetles by 25%.

e Viruses

Most virus research is still in early stages of development, and there are only two viruses presently being studied by ARS scientists that can be expected to reach commercialization within the next 5 years: the Heliothis virus, which has already been registered by EPA, and the alfalfa looper virus which has shown considerable promise in early studies. Both of these viruses will be discussed at more length in sections to follow. In addition, one virus is being studied intensively by the Forest Service in cooperation with ARS scientists, and if early trials are successful, this virus could be widely used in 5 years. Other viruses show promise, and particularly, if the Heliothis, alfalfa looper, or gypsy moth virus are successful and pave the way, some of these could reach commercialization within 10 years.

Much of the virus research for the next 5-10 years will be devoted to accumulating the mass of basic knowledge that is needed if viruses are to be exploited properly. It must be determined how the virus penetrates a susceptible cell, how it directs the cell to make new virus, and how the new virus is released from the infected cell. Much of this work will have to be carried out in tissue culture, and it will be necessary to develop the necessary technology to do this. It is to be expected that the necessary knowledge will be successfully accumulated during the next 5-8 years, and after that rapid progress will be made in the development of practical commercial formulations of insect viruses.

i Heliothis virus. Since the Heliothis virus is already in the hands of at least one company that is considering marketing it for "population control" in cotton, some of the visualized technology will be developed by industry. However, if extensive progress is to be made, much of the research will have to be done by aRS. If the expected studies are completed, it can be expected that, during the next 5 years, the cost of producing Heliothis virus in mass-reared insects will be reduced by 50-75% and that improved formulations enhancing the effectiveness of the virus will have been prepared. These formulations will incorporate materials to stabilize the virus in storage and after application in the field and may incorporate feeding stimulants and baits to increase the likelihood of the virus being eaten by the pest insect. While considerable progress has been made toward improving the virus and making it effective, more needs to be done so that the present expected market must be small. However, sales should grow gradually during the next 5 years, with perhaps 5% of the treatments for control of Heliothis being made with virus 5 years from now. Assuming a material cost of $3/application, then the retail value of sales of the virus should approach the $1 million mark. If further improvements in the virus formulation and application procedures are successful, then by the end of 10 years, it could be expected that the virus could enjoy 25% of the market or more, with retail sales exceeding $5 million.

ii Cabbage looper virus. Effective formulations of the cabbage looper virus can be prepared now at an economical cost. However, the market is relatively small, and effective control agents (both chemical and biological) are available, so little industrial interest in this virus exists. Furthermore, the alfalfa looper virus, to be discussed in the next section, may be able to substitute for the cabbage looper virus. Consequently, little advance in technology of this virus can be expected during the next 5 years. If other viruses prove successful, and if the alfalfa looper virus proves unable to replace this virus, then some development of the cabbage looper virus for use commercially could occur sometime between 5 and 10 years from now. There should be no obstacles to its registration.

iii Alfalfa looper virus. It should be possible to produce this virus economically within 5 years. Also within 5 years effective formulations of the virus should have been developed. Within 10 years a tissue culture method of producing the virus should become practical. Safety tests should have been completed and a Temporary Exemption from the Requirements for Tolerance should have been granted within 5 years. By the end of 5 years, widespread testing of the virus should be well underway and, if these are successful, the virus should be being sold commercially within 7 years.

iv Alfalfa caterpillar virus. Little work has been done yet with this virus. However, it should be relatively easy to produce and within 5 years after research has begun on this insect, commercialization would be possible. It is doubtful that this will occur unless the Heliothis or alfalfa looper viruses lead the way, so little progress can be expected within the next 5 years, with possible commercialization within 10 years.

v Granulosis virus of Indian meal moth. This virus could have potential for long-term control of larvae of the Indian meal moth. Work is proceeding slowly because of a shortage of manpower, but it could be expected that by 5 years techniques will have been developed for producing this virus in large quantities economically enough for use in control of this pest. Field evaluation should be well advanced by the end of 5 years so that a reasonable determination of the potential of this virus can be made. If results have been good, commercialization of this virus could be completed in 10 years, although here too, further development will depend to a large extent as to how well work with the Heliothis virus, the alfalfa looper virus, and the gypsy moth virus has stimulated industry to pursue these agents.

vi Nuclear polyhedrosis virus of mosquitoes. Little progress in the development of this virus can be expected in the next 5 years. However, the virus does hold promise and further work should be planned. Some improvements in the production methods for this virus may be made in the next 5 years, but major steps forward may depend on the development of suitable tissue culture procedures.

f Tissue culture. At present, all insect viruses must be produced in living insects--not a convenient procedure. It would be very desirable if a fermentative procedure could be devised to produce these viruses free of the host insect. The only known alternative to the insect is through the use of "tissue culture," in which cells of the insect are grown free of the parent in specialized media which allow the cells to develop under artificial conditions. At present, insect cells can be grown in this manner, but the foods or "nutrients" that must be combined to make up a suitable medium to grow these cells are very expensive, coming from such exotic sources as insect or calf sera. However, considerable progress has been made in finding less expensive nutrients to use in these media, although much work remains to be done. Most researchers believe that economical tissue culture media will be developed, although the research will be difficult. If the work is successful, it could make the production of insect viruses much less expensive, so that tissue culture would become the method of choice for the production of these agents.

Tissue culture experimentation is also necessary in order to learn how viruses infect insects and why they infect some species and not others. We know that insect viruses have a limited host range and are not harmful to other forms of life, but we do not know why. To understand this, it will be necessary to intensify research into how viruses infect and replicate in the insect. Tissue culture offers the most satisfactory tool for doing this. This research should not be confined to the nuclear polyhedrosis virus, but should be extended to cover all groups of insect viruses that have shown potential for pest control.

A practical tissue culture procedure for the production of insect viruses would mark a major step forward. Continued progress can be expected throughout the evaluation period, with a major breakthrough probably occurring at some time between 5 and 10 years. When this breakthrough is reached, the findings should be applicable to the production of many insect tissues free from the insect and, consequently, to the production of many different insect viruses.

g Formulation. Much needs to be learned about factors that reduce or enhance the effectiveness of viral agents in the field. For example, nuclear polyhedrosis viruses are protected by being encased in an inert protein crystal. Yet, they die in a surprisingly short time in the field, particularly when applied to cotton. Sunlight can kill viruses and probably contributes much to this rapid death, but other factors are involved. Viral formulations now contain buffers, stickers, and physical shields such as particulate matter (clays or carbon), or plant pigments. However, we need to know more about how to protect these viruses.

The viruses are only effective in the field when eaten. Thus, it could be valuable to incorporate baits into a viral formulation to attract the pest insect into eating the virus, or to incorporate feeding stimulants to induce them to eat more virus. This method of enhancing the effectiveness of viral formulations needs to be explored.

Satisfactory means of formulating the various insect viruses are needed. During the next 5 years, continuous progress should be made. The value of encapsulation should be known. The incorporation of stabilizing agents should have been developed to a point where stability is a minor problem with many viruses. The use of baits and feeding stimulants should have been explored in the case of a few viruses, particularly those destined for use on such crops as cotton where the habits of several major insect pests make them difficult to infect with virus. These studies, continued throughout the 10-year period, should enable evaluation of the effectiveness of the various viruses selected for study under optimum conditions.

h Screening and identification of viruses. There are continuing searches for new viruses, both within the U.S. and abroad. Also, foreign exploration scientists seeking parasites and predators are sending any viruses they find to the U.S. for study. This program should be continued, and, in conjunction with it, it is important that basic work should be carried out to better identify these viruses.

i Genetics of viruses. Better knowledge of the genetics of viruses and their mutability is needed. Already, there is evidence that these viruses have a very low rate of mutation (using virulence as a marker) although virulence was changed in one case (fall armyworm virus) apparently permanently, by passage of the virus with a carcinogenic agent through the host insect.

j Integrated pest control. Microbial insect control agents fit ideally into an integrated pest control program. Parasites and predators, as well as adult pests, are not susceptible to most microbes. Therefore, control of pests with microbial agents should not interfere with other aspects of an integrated control program, such as release of parasites, predators, or sterile males. The next 5 years should see an increasing coordination between the various fields of crop protection -- including the use of parasites and predators, chemical control, sterile male releases, and plant resistance. Effective combinations of these approaches will probably not appear until after the 5-year period, but should be increasingly used thereafter.

3 Weed biotic agents except pathogens.

a Target weeds will be selected on the basis of an analysis of the most efficient probable type of control (i.e., introduction of exotic control agents, augmentation of agents presently in the U.S., chemical, mechanical, or a combination of these methods). Research to augment the effectiveness of control agents may be initiated when suitable exotic control agents cannot be found, when introduced exotic and/or indigenous agents are less effective than required, or when control is desired only in certain locations or at certain times, etc. Development methods of remote sensing will be made to measure weed infestations. Objectives are to evaluate 1 additional weed per SY each year as a possible candidate for augmentation.

b Improvement of ability to estimate the impact of presently occurring control agents on the weed, to measure the key factors regulating the effectiveness of the major controlling agents, and to find points in the present regulating system that can be manipulated to increase the amount of control. Objectives are to analyze the impact of the controlling agents on 1 weed each 2 SYs.

c Development of improved means of augmenting the numbers of biotic suppressants of weeds by such methods as:

i Distribution from areas of surplus to areas where they cannot survive the year round, or at times of the year when they are not sufficiently abundant.

ii Developing methods of mass rearing biotic suppressants in the laboratory on host plants, or on artificial diet in sufficient numbers, and at a low enough cost to provide economical control.

iii Reducing the effect of mortality producing factors in the field such as parasites, predators, and pathogens of the suppressants.

d Development of methods of manipulating the agro-ecosystem to increase the control provided by suppressants, such as:

i Increasing the competition from other vegetation.

ii Integrating the use of chemical and mechanical controls with biological so that weeds are controlled at times of the year, or in ecological situations where the suppressant alone does not provide sufficient control.

iii Fertilizing or applying chemicals to increase the acceptability and buildup of the suppressant organisms.

e Development of methods of conserving suppressant populations in the field such as:

i Timing of insecticide applications aimed at

insect enemies of crops to minimize mortality to weed-feeding insects.

ii Providing requisites in short supply such as alternate hosts or food plants of weed-feeding insects.

iii Modification of planting dates, crop rotations, and other cultural practices to favor suppressant population.

f Improvement of methods of assessing the effectiveness and benefit derived from the applied controls.

Objectives are to develop methods of controlling a weed pest by augmentation of the effectiveness of its enemies within 5 years and to control 3 weeds within 10 years. In each case, damage caused by each weed (economic, area infested, cost of control, etc.), should be reduced by 50% within 10 years.

4 Weed pathogens. The discovery, development, and utilization of indigenous plant pathogens for weed control may constitute the basis for a new type of herbicide industry within the next 10 years. This method of weed control will be expedited by the computerization of worldwide data on plant pathogens and their hosts; this would include the data from the USDA National Fungus Collection (Host Index of Plant Diseases), the Index of Fungi, Saccardo's Sylloge Fungorum and Oudeman's Enumeratio Systematica Fungorum. New data will be placed in the system as soon as available.

a Reduce losses in rice and soybeans due to northern jointvetch by 50% through the use of a fungal herbicide (5 years).

b Reduce losses in cotton and soybeans due to prickly sida by 5% through the use of a fungus disease (10 years).

c Reduce infestations of strangle vine in citrus trees in Florida by 90-95% through the successful development of pathogen (Phytophthora citophthora) herbicide (10 years).

d Reduce significantly interference of waterhyacinth with navigation, irrigation and recreation uses of water in Florida, Louisiana, and Georgia through the combination of weed pathogens with weed-feeding insects and fish (10 years).

5 Antagonists of plant pathogens.

a There is a growing list of examples of "pathogen suppressive" soils that either do not allow establishment of certain pathogens unless sterilized first, permit establishment of pathogens but suppress disease development or permit disease initially but then support a natural biological control with resultant disease decline. Greater effort is needed to more reliably identify and/or promote such pathogen-suppressive soils for expanded or more effective disease control in sites presently recognized as conducive to disease. Such sites may also provide a wealth of antagonists for introduction to other areas.

i Reduce avocado, cotton, apple, pear, strawberry, wheat, alfalfa, tobacco, potato, pea, bean, soybean annual yield losses caused by cortical rotting fungi by 5% through the development of soils microbiologically suppressive to soil pathogens such as Rhizoctonia, Fusarium, Pythium, or Phytophthora (10 years).

b Increased effort is needed to improve systems whereby organisms related to pathogens can be safely applied commercially to trigger host resistance to pathogens, or nullify virulence in pathogens. Successful biological control by this approach is possible for several diseases within the next 10 years.

i Restore the use of the chestnut tree species for shade and other purposes by controlling the Dutch elm disease and the chestnut blight fungus by antagonists of the former and hypovirulent strains of the latter (10 years).

c An accelerated effort is needed to develop new or improved and more reliable management systems that will permit greater use of resident antagonists in biological control of soilborne pathogens particularly. In addition, a greater effort is needed in the design of systems whereby antibiotic organisms, hyperparasites, or competitive organisms can be introduced and established on leaves, in floral parts, on seeds, on roots, or in other infection courts and thereby protect against pathogen attack. Since some antagonists display specificity towards various root pathogens, and are present in or may be established in only certain soil ecosystems, selection of potentially beneficial microorganisms for biological control tests in the field must be made on accumulated knowledge and current research on each system. At current levels of research effort a minimum of 10 years is necessary for the development of a usable technology for controlling one or two soilborne diseases.

i Increase potato yields in the irrigated West by 50 cwt/acre and eliminate current soil fumigation practice costing $100/acre through control of Verticillium wilt (10 years).

ii Increase yields of peas and tomatoes by 25-50% through control of Fusarium wilts. Also decrease the massive programs in the private and public sectors on breeding for resistance and allow return to certain preferred varieties which are susceptible to Fusarium (10 years).

C Research Approaches

1 Parasites and predators.

a Develop pesticide use systems and pesticide application techniques that have minimal effect on natural enemies in all areas where pesticides are used, or potentially used on a large scale such as cotton, fruit, citrus, vegetables, soybeans, grain sorghum, and corn.

i Identify pesticides having the least detrimental effects on natural enemies, but being effective against target pests (NCR-Columbia, MO; SR-Stoneville, MS, 20230 and 20240; Houma, LA, 20240; College Station, TX, 20230; Weslaco, TX, 20220; NCR-Ankeny, IA, 20240).

ii Determine the best methods for applying insecticides, but avoiding contact with natural enemies of target pest(s) (locations same as above).

b Develop plant varieties resistant to pest populations, but having minimal impact on natural enemy populations with particular emphasis on crops such as cotton, soybeans, wheat, grain sorghum, corn, alfalfa, and sugarcane.

i Compare development of natural enemies reared on host/prey-fed resistant and nonresistant plants (SR-Stoneville, MS, 20230 and 20240; Brownsville, TX, 20230; Houma, LA, 20240; NCR-Lafayette, IN, 20240; Ankeny, IA, 20240; Lincoln, NB, 20240; WR-Phoenix, AZ, 20230).

ii Compare predator-parasite populations quantitatively and qualitatively in resistant and nonresistant plant populations in the field (Locations same as above).

c Develop methods for mass producing and distributing natural enemies such as *Trichogramma* spp., *Microplitis croceipes*, *Reesimermis nielseni* and other selected parasitic nematodes, *Opius* spp., *Lixophaga diatraeae*, *Jalysus spinosus*, *Brachymeria intermedia*, *Pediobius foveolatus*, *Spalangia endius*, and *Amitus hesperidum* for use in augmentation programs for control of pests such as *Heliothis* spp., pink bollworms, mosquitoes, fruit flies, *Spodoptera* spp., sugarcane borer, plant bugs, tomato hornworms, tobacco budworms, cabbage loopers, gypsy moth, Mexican bean beetles, muscoid flies, and citrus blackflies.

i Develop mass-rearing programs based on habitual or nonhabitual hosts/prey (NCR-Columbia, MO; WR-Tucson, AZ; SR-Lake Charles, LA; Stoneville, MS, 20230 and 20240; College Station, TX, 20230; Tifton, GA, 20240; Oxford, NC, 20230; Brownsville, TX, 20230; Weslaco, TX, 20220; Gainesville, FL, 20480; WR-Phoenix, AZ, 20230).

ii Develop artificial diets for mass-rearing entomophages such as *Trichogramma* spp. and other hymenopterous and tachinid larval parasites and a parasitic nematode (NCR-Columbia, MO; SR-Baton Rouge, LA, 20230; Gainesville, FL, 20250; NCR-Fargo, ND, 20250).

iii Establish guidelines and techniques for the selection of appropriate strains of mass reared entomophages (NCR-Columbia, MO; WR-Tucson, AZ; SR-Stoneville, MS, 20230 and 20240; Tifton, GA, 20240; College Station, TX, 20230; Gainesville, FL, 20250).

iv Develop quality control criteria for measuring and maintaining the quality of laboratory-reared entomophages. (Locations same as above).

d Develop the augmentation concept as an established control procedure in crops such as cotton, vegetables, sugarcane, soybeans, and tobacco for pests such as Heliothis spp., plant bugs, cabbage looper, sugarcane borer, Mexican bean beetle, tomato hornworm, and citrus blackfly.

i Conduct studies using beneficials in combination with behavioral chemicals and/or food (NCR-Columbia, MO; WR-Tucson, AZ; SR-Stoneville, MS, 20230 and 20240; College Station, TX, 20230; Tifton, GA, 20240; Oxford, NC, 20230; Gainesville, FL, 20250).

ii Conduct studies developing release techniques, timing, and minimum rates. (Locations same as above).

iii Conduct pilot test studies to demonstrate the efficacy and economics of the concept. (Locations same as i).

e Develop economical artificial foods that may replace the host, pollen, or honeydew that will retain, arrest, and/or sustain the predator/parasite population.

i Screen artificial foods for attractancy, arrestment, sustaining ability, and oogenesis against key predators and parasites (NCR-Columbia, MO). Related NRP's -20240 and 20250.

ii Conduct cage, small plot, and field trials to determine effectiveness of the foods (NCR-Columbia, MO). Related NRP's-20240 and 20250.

f Develop and improve knowledge of behavioral chemicals, their role in host-parasite and prey-predator relations, and develop procedures for using these chemicals to obtain maximum efficacy of the parasite/predator (NCR-Columbia, MO; SR-Stoneville, MS, 20230 and 20240; Baton Rouge, LA, 20230; Tifton, GA, 20240; Gainesville, FL, 20250; NCR-Fargo, ND, 20250).

i Identify and synthesize and/or collect behavioral chemicals.

ii Develop methods for using behavioral chemicals.

(a) Local programs.

i Evaluate prestimulation of released beneficials with behavioral chemicals to stabilize and orient them at time of release.

ii Evaluate treatment of plant surfaces with behavioral chemicals for stimulation of natural and/or released beneficials.

(a) Supplying appropriate chemical from host or prey insect to elicit and maintain effective search.

(b) Supplying appropriate chemical from host plant for intercepting and activating search, in what would otherwise be refuge areas.

(c) Evaluate the integration of specific behavioral chemicals with food sprays and/or artificially supplied host or prey-insect material.

(b) Regional Program - Evaluate application of appropriate behavioral chemicals on selected host plants throughout an area for suppression of total pest population.

g Develop methods for altering agroecosystems involving crops such as cotton, tobacco, soybeans, sugarcane, grain sorghum, wheat, and corn to the entomophage's advantage.

i Determine if strip-cropping is feasible when economics and additional energy requirements are considered (NCR-Columbia, MO; WR-Tucson, AZ; SR-Stoneville, MS, 20230 and 20240).

ii Determine if housing can be practically and effectively provided for entomophages (WR-Tucson, AZ; SR-Oxford, NC, 20230).

h Develop models of host-parasite or predator prey interactions (NCR-Columbia, MO; WR-Tucson, AZ; SR-Stoneville, MS, 20230 and 20240; College Station, TX, 20230; Gainesville, FL, 20250 and 20480; Tifton, GA, 20240; Oxford, NC, 20230; Lake Charles, LA, 20480).

i Intensively study beneficials and host or prey determining ecological, physiological, and ethological interactions.

ii Determine abiotic and biotic factors that enhance or limit the effectiveness of the beneficials.

iii Determine how beneficials regulate host/prey populations.

iv Develop methods for qualitatively and quantitatively placing values on predators and parasites within agroecosystems.

2 Insect pathogens

a Bacteria

i *Bacillus thuringiensis*. In every case in which search is made for either better formulations of a δ-endotoxin against a particular insect species or for a new toxin produced by *B. thuringiensis*, the basic approach will be the same -- the principal difference being in the assay organisms used to measure progress in research.

(a) Collect as wide a variety of isolates of *B. thuringiensis* as possible, seeking cultures from all over the world. (SR-Brownsville, TX).

(b) Grow all isolates collected in identical media, under standard conditions of temperature and aeration, in submerged culture on a rotary shaker; recover the toxin produced using the acetone-lactose coprecipitation process, preparing a dry formulation of the toxin; screen all formulations so prepared against as wide a variety of insect species as possible; select those isolates producing formulations with the highest activity against one or more desired target insects for further study (SR-Brownsville, TX; NCR-Peoria, IL).

(c) Analyze the spectra of activity of the toxins produced by each isolate in order to determine the most suitable insect to use in the bioassay of the toxin in further studies. (SR-Brownsville, TX; NCR-Peoria, IL; Manhattan, KS, NRP 20620).

(d) Subject cultures selected as the most promising to standard fermentation studies, growing them on various fermentation media at varying conditions of temperature, pH, and aeration, so as to find conditions to maximize the production of the desired toxin. In the case of these toxins that are not δ-endotoxins, levels of toxin should be compared in both the usual acetone-precipitated formulation, but also in the supernatant of the centrifuged beer in order to decide on the best way to recover the toxin from the fermentation. (SR-Brownsville, TX).

(e) Safety testing of a preliminary nature should be undertaken for any toxin produced by _B. thuringiensis_ that is neither δ-endotoxin nor β-exotoxin, using mice as test animals. (None).

(f) Study the stability and efficacy of formulations in the laboratory and the greenhouse. If necessary, modifications should be made in the compositions of the formulations to make them more satisfactory for use. If it is planned to incorporate the toxin into feed (for example, β-exotoxin-like materials for the control should be begun at this time. (For protocols, see Section 'e' (viruses)). (SR-Brownsville, TX; Kerrville, TX, NRP 20480; NCR-Columbia, MO).

(g) All new formulations deemed safe should then be produced in sufficient quantity for field trials in suitably sized plots. If the first plot tests appear promising, the required safety tests should be carried out (see Section 'e' (viruses)), and the field trials should be expanded and repeated at as many different locations as possible. (SR-Brownsville, TX; Savannah, GA, NRP 20620; NCR-Columbia, MO, Manhattan, KS, NRP 20620; Ankeny, IA, NRP 20240; WR-Fresno, CA, NRP 20620).

(h) Further development would probably best be carried out by industry.

ii _Bacillus sphaericus in the control of mosquito larvae_. _Bacillus sphaericus_ is presently being evaluated in field tests against mosquitoes. If the results are promising, then research similar to that described for _B. thuringiensis_ should be carried out. (NER-Beltsville, MD).

iii <u>Bacillus popilliae in the control of Japanese beetles</u>. Research to determine the reason for the inability of *B. popilliae* to produce infective spores in artificial media should be continued. Since the usual methods of developing submerged fermentations have been tried with this organism without success, basic studies on the physiology of *B. popilliae* should be stressed. The fact that the bacterium does not produce competent nucleic acid should be investigated to see what influence this phenomenon has on sporulation. Other sophisticated techniques, such as transformation of nucleic acid should be applied as needed. (NCR-Peoria, IL).

Other strains of *B. popilliae* should be investigated in connection with these fermentation studies. This is particularly important in the case of *B. popilliae* because the strain of bacterium now used for production of the organism in the living insect is of medium virulence. This strain was selected so as to allow the diseased insect to live longer and thus maximize the production of infective spores. There are more virulent strains of *B. popilliae* available, and once ways of producing infective spores in fermentation tanks are found, then these more virulent strains should be tested to see if they would be more effective in the control of the Japanese beetle in the field. (NER-Beltsville, MD; NCR-Peoria, IL).

iv <u>Other bacteria as microbial insect control agents</u>. The soil contains, literally, millions of varieties of bacteria, fungi, and actinomycetes. A screening program should be initiated to find those that produce safe, useful, insecticidal agents. While the primary screening should be for actinomycetes, such a program could very likely find bacteria that produce insecticides, and these should not be overlooked during the screening. Details of the program will be discussed under actinomycetes (Section "c") (SR-Brownsville, TX).

<u>b Fungi</u>

i Devise and improve bioassay techniques to determine infectivity and virulence (NCR-Columbia, MO).

ii Devise methods to detect presence, dispersion in the environment (NCR-Columbia, MO).

iii Devise and perfect fermentation production systems (NER-Orono, ME, NRP 20220; NCR-Columbia, MO; SR-Lake Charles, LA, NRP 20850).

iv Devise means of increasing longevity of fungal spores; stability of formulations (NER- Orono, ME, NRP 20220; NCR-Columbia, MO).

v Test safety and efficacy in small, large plot tests (NER-Orono, ME, NRP 20220; NCR-Columbia, MO; SR-Lake Charles, LA, NRP 20850).

vi Determine occurrence of fungal toxins. (NCR-Columbia, MO.)

c Substances produced by actinomycetes

i Expand and further improve the screening techniques already developed at the Brownsville laboratory so as to be able to test the production of toxin by approximately 500 isolates of actinomycetes/week, testing the activity of these possible toxins against 2 to 4 test insects.

ii Regrow and retest those cultures that appear to produce toxin, grow cultures with confirmed activity on a larger scale and screen the chemical properties of the toxins so as to select those that are easiest to recover from the fermentation beers.

iii Produce these selected toxins in small quantities and determine the spectrum of insecticidal activity in laboratory tests.

iv Conduct preliminary tests for acute mammalian toxicity in mice, select those toxins that have the best ratio of insect to mammalian toxicity for further study.

v Continue purifying the toxin from each selected strain and develop methods for measuring its activity.

vi Select the cultures producing the most promising toxins and develop suitable fermentation and recovery processes to produce enough material for greenhouse tests; the toxicity of any material looking promising in the greenhouse should be examined in more detail, and if the evaluation of these data is satisfactory, then sufficient material should be produced for small-scale field tests. (SR-Brownsville, TX).

d Protozoa

i *Nosema locustae* in the control of grasshoppers.

(a) Increase the yield of spores of *N. locustae* from infected grasshoppers from the present 2 billion to an average of 8 billion/grasshopper.

(b) Improve the viability of the spores in storage, perhaps by storage under liquid nitrogen.

(c) Refine both the formulation of the spore preparation and the aircraft delivery system used to disperse it so as to increase the efficiency of the distribution of spores and reduce the per acre cost. Other species of *Nosema* should be examined. Two are known, but it has been difficult to produce high levels of spores of these two species. Recent developments have indicated that producing the spores in an alternate host might solve this problem, and further research along these lines should be undertaken. (WR-Bozeman, MT, NRP 20250).

ii Nosema algeriae. At present, little or no research is being done with N. algeriae, but a preliminary evaluation of the use of this organism for the control of mosquitoes is planned. The amount of further research effort applied and the approaches to be used will depend on the results of this evaluation. (None).

iii Nosema pyrausta and Mattesia tragoderma.

(a) Develop methods for production of spores and for maintaining spore viability. (NCR-Ankeny, IA, NRP 20240; Madison, WI, NRP 20620).

(b) Develop methods for bioassay of promising isolates of the pathogens. (NCR-Ankeny, IA, NRP 20240; Madison, WI, NRP 20620).

(c) Test safety of pathogens for non-target organisms. (NCR-Madison, WI, NRP 20620).

(d) Test efficacy of pathogens in small and large scale trials. (NCR-Ankeny, IA, NRP 20240; Madison, WI, NRP 20620).

e Viruses. There are many research approaches that are common to the study of all insect viruses, and, with the exception of those specifically involved in the studies on tissue culture and formulation, these will be grouped together here and not discussed under the individual viruses.

i Develop means of standardizing the virus. Before any detailed studies can be done on the production, recovery, or use of any virus, means must be devised to accurately measure the activity of a virus preparation or formulation. Such tests must permit evaluation not only of how much virus material is present in a preparation, but also of how virulent or viable it is. (NCR-Columbia, MO; SR-Brownsville, TX, Tifton, GA, NRP 20240; WR-Phoenix, AZ, NRP 20230).

ii Search for more economical ways of mass-rearing host insects. At present, there is no way to produce virus economically except in a living insect. Thus, the first stage in the development of any virus is to find a way of minimizing the cost of mass-rearing the host insect. Some viruses will infect more than one insect, and in such cases, the search must include comparisons of the cost of rearing alternate host insects. The search should include evaluation of various insect diets, rearing containers, and environmental conditions in the rearing chambers. It should be noted that the conditions for optimum production of virus within an insect may not coincide with the conditions for optimum growth of the insect. Separate procedures may be required for maintenance of a stock culture and for production of virus. (SR-Brownsville, TX; Tifton, GA, NRP 20240; Stoneville, MS, NRP 20240; WR-Phoenix, AZ, NRP 20230).

iii Develop recovery procedures. Inexpensive means of harvesting diseased insects and recovering virus from their carcasses have to be devised. In these studies, there will have to be a careful evaluation of the final product to make sure that the ability of the virus to survive in storage has not been harmed by the recovery procedure. (SR-Brownsville, TX; Tifton, GA, NRP 20240; WR-Phoenix, AZ, NRP 20230).

iv Study factors involving the survival of the virus in nature. Develop methods to detect presence of virus and to evaluate virus stability and survival. (NCR-Columbia, MO).

v Determine the safety of the virus. Before permission for any widespread testing of a virus formulation will be granted, the Environmental Protection Agency must be satisfied that the virus is safe to use. The EPA has devised a general protocol for safety testing of viruses. This includes: Single dose feeding tests, eye irritation studies, dermal toxicity and skin irritation, inhalation studies, human, primate and nonprimate tissue culture studies. There must be a 90-day feeding study in at least two species, one a non-rodent, also skin sensitization and respiratory sensitization and inhalation toxicity. The host spectrum of the insect virus must be determined. These studies should include honeybees and other beneficial or aesthetically and commercially important invertebrates as well as parasites and predators of the target insect. The effects of the virus on fish and other aquatic vertebrates must be determined, as well as tests on two species of birds, one of which must be an insectivorous species. At present, tests of pathogenicity of these viruses to plants need not be conducted, but observations of phytotoxicity must be made during field tests. (NER-Beltsville, MD; NCR-Columbia, MO).

vi Determine the efficacy of the virus. Early field tests of virus materials will have to be conducted in small plots. However, it should be realized that in such small plots the possible beneficial interaction between the virus and the normal beneficial insect populations (parasites and predators) will undoubtedly be destroyed by nearby chemical treatments. Therefore, it is very desirable, as soon as possible, to conduct trials of virus materials in large plots far enough isolated from chemically-treated fields that the combined effect of virus and beneficial insects can be explored. (NER-Beltsville, MD; NCR-Columbia, MO; WR-Phoenix, AZ, NRP 20230; SR-Tifton, GA, NRP 20240).

vii Search for more virulent strains of the virus. Once a virus has been determined to be useful, then considerable basic research is warranted. A survey of related viruses should be undertaken to see if more virulent strains can be found. Passage of the virus through susceptible insects, possibly coupled with mutagenic agents, should be attempted to see if a strain with increased virulence can be produced. (NER-Beltsville, MD; NCR-Columbia, MO).

Heliothis virus. Since this virus has reached the stage of commercialization, minimum developmental work is required. Some studies are planned to see if the cost of production can be reduced, some tests will be carried out to examine the causes of the instability of the virus on cotton leaves, and cooperative field tests with industry will be continued. (SR-College Station, TX, NRP 20230).

Cabbage looper virus. Only minimal research on the cabbage looper virus should be undertaken until results of studies with the alfalfa looper virus have been evaluated. If the latter virus fails to prove to be as effective as the cabbage looper virus, then some studies on the combination of the use of the looper virus and of B. thuringiensis should be undertaken. (NER-Beltsville, MD); isolate activity, host strain differences, epizootic studies (NCR-Columbia, MO).

Alfalfa looper virus. The field testing now underway using this virus in insect control on cabbage, soybeans, and cotton should be extended to 1-acre plots so as to further evaluate its efficacy. If results continue promising, then attempts should be made to obtain a Special Permit from the EPA to allow more widespread testing. Safety tests should be continued to obtain a Temporary Exemption from the Requirements for Tolerance from EPA. Preliminary investigations into the use of the alfalfa looper virus against the European corn borer should be initiated, possibly in combination with a bait. Causes of the instability of this virus on crops, particularly on cotton, should be investigated so as to develop formulations capable of counteracting this instability. Further research should be carried out to reduce the cost of producing this virus in insects and to improve the recovery and formulation of the viral product. Attempts to develop economical methods of producing this virus in tissue culture should be intensified. (NER-Beltsville, MD; WR-Phoenix, AZ, NRP 20230).

Alfalfa caterpillar virus and Granulosis virus of Indian meal moth. Each virus can be produced in its host insect. Both viruses should be studied according to the general principles outlined in the introduction to this section. (WR-Fresno, CA, NRP 20620).

Nuclear polyhedrosis virus of mosquitoes. While this virus seems to hold some promise, it is very difficult to produce in mosquitoes. At present, little work is being done with this virus, but, when the manpower becomes available, sufficient virus should be produced to allow a limited evaluation of its potential for mosquito control. Further work would depend on the results of this evaluation, but, if the research appears warranted, attempts should be made to mass-produce this virus, either in the mosquito or in tissue culture, following which further research should be conducted along the principles outlined in the introduction to this section. (None).

e General

i Tissue culture

(a) Production of insect cells. The first step in any tissue culture research is to develop adequate means of producing the insect cells. The medium used can be expensive when limited numbers of cells are being used for basic research into virus multiplication and similar areas, but must be cheap when used for commercial production of virus formulations. Present media are suitable for basic research, but are much too expensive for virus production. Intensive research must be directed at lowering the cost of tissue culture media. (NER-Beltsville, MD).

<u>(b) Production of virus in tissue culture</u>. The two viruses most intensively studied at present are the alfalfa looper virus and the gypsy moth virus. Both viruses should be studied in tissue culture, with attempts being made to progress from roller bottles to fermentation vessels. Attempts should be made to determine the optimum environmental conditions for production of the virus. Such efforts may entail modifications in fermentor design. The stability of the viruses under these conditions must be studied, particularly to ensure that there are no mutations in the virus nor any loss of virulence under these conditions. Methods of recovering and formulating virus produced in tissue culture must be studied. As suitable techniques for the production of these two viruses are developed, efforts should be made to expand them to other important viruses. (NER-Beltsville, MD; WR-Phoenix, AZ, NRP 20230).

<u>(c) Basic studies on viral multiplication and infection</u>. At the cellular level a virus infection can be differentiated into four stages: 1) penetration of a susceptible cell; 2) uncoating of the viral nucleic acid; 3) synthesis of new viral components and the assembly of progeny virus; and 4) release of infectious virus progeny from the infected cell. Tissue culture studies should be extended to examine these stages, using biochemical techniques and the electron microscope, to try to find how the virus is able to develop. Research should first be carried out in a wholly susceptible host, i.e., a host in which the virus' replication leads to completely formed infectious polyhedra. These studies should determine which of the enzymes required for the synthesis of viral components are carried by the virus or coded for in the viral genome and which are present in any susceptible cell. It must also be determined if specific structures either within the infected cell or on the progeny virion are required for virus assembly and the incorporation of virions into forming polyhedra. Such studies should be applied to any virus of significance in the control of insects, but should first be applied to the alfalfa looper virus and the gypsy moth virus.

Tests in tissue culture have shown that there are factors which act at the cellular level to help determine the host range of the virus. It has also been demonstrated that cells which do not produce polyhedra after exposure to a virus and thus are apparently not infected, may, in fact, be susceptible to infection but do not support a complete cycle of virus replication. Since this could have significance in the safe use of viruses, research should be continued into the mechanisms involved in this aspect of virus infection and replication. In those systems where some type of infectious material is produced, the nature of the infectious material (nucleic acid, nuclear protein, complete virion) must be determined. Also, the host range of these abnormal particles should be compared with that of normal particles. Methods must also be developed for detecting incomplete replication of non-infectious particles as well. Also, the effects of such particles, if any, on cell metabolism must be determined. (NER-Beltsville, MD). Also to be determined are mode of virus applications <u>in vitro</u> and <u>in vivo</u>; <u>in vivo</u> host spectrum, serology, radio-immunology. (NCR-Columbia, MO).

(d) Basic studies on insecticidal toxins. Tissue cultures offer the opportunity to examine the reactions of insects to various insecticidal toxins on a cellular level. Since a basic understanding of these reactions could enable us to use these toxins more effectively, tissue culture studies chould be undertaken when possible. Particular attention should be directed toward the reaction of insect cells to δ-endotoxin from B. thuringiensis and to the various subunits of this protein. (None).

ii Formulation

(a) Stabilization. All formulations of microbial insect control agents should be studied for stability in storage and in the field after application. Most agents will need to be protected from sunlight, a very effective germicide, and attention will have to be directed towards the development of shields against these harmful rays. Many agents will be sensitive to pH, and particular attention will have to be paid to this problem in the search for satisfactory wetting agents and stickers. The effect of the pH of dew on residues of these substances must be studied, possibly incorporating buffers to protect the agent. The surface of a plant leaf is not inert, and the action of the leaf on the insecticidal material or the microbe must be investigated. This should not be restricted to the leaves of a given plant species, but should be directed toward the leaves of any type of plant on which the microbial material might be applied. (NER-Beltsville, MD; NCR-Columbia, MO; SR-Brownsville, TX; Stoneville, MS, NRP 20240).

(b) Baits and feeding stimulants. Most microbial agents (and this includes the infective agents such as the viruses and the toxins produced by B. thuringiensis) must be eaten to be effective. Anything that will increase the likelihood (or the quantity of) these agents being eaten will improve the efficacy of the product. Thus, the use of baits and/or feeding stimulants should be investigated for incorporation into the formulations of any microbial agent. This should be particularly emphasized where, as in the case of cotton, the habits of the insect are such as to reduce the likelihood of its feeding on the agent. (NCR-Columbia, MO; SR-Brownsville, TX; College Station, TX, NRP 20230; WR-Phoenix, AZ, NRP 20230).

iii Screening and identification of viruses. The search for new viruses (and other insect pathogens) should be a continuing one. All possible sources of new agents should be exploited and considerable reliance should be placed on foreign and domestic entomologists working on cooperative programs with the ARS. To help these cooperators, many of whom will not be trained in entomology, a handbook should be prepared to show them how to collect and handle diseased insects, and, where possible, to isolate the pathogen for transmission to suitable laboratories in the U.S. (NER-Beltsville, MD; NCR-Columbia, MO).

iv Genetics of viruses. Considerable effort is warranted to learn more about the genetics of viruses. Some of this work can be done in the living insect, using virulence as a marker; other work should be done in tissue culture, using plaque formation and infectivity as markers. (NER-Beltsville, MD; NCR-Columbia, MO).

v Application of microbial insect control agents to crops. As mentioned earlier, it is very important to the successful use of microbial insect control agents that good coverage of the crop or trees be obtained. Among the factors to be considered are: droplet size, dispersion, volume of spray to be applied/acre, methods of obtaining good underleaf coverage, and the choice of types of spray: mist, ultra-low-volume, and conventional. The spraying apparatus must be considered, and, in the case of aerial applications, the optimum height of the spray plane. All these should be considered in conjunction with the various developments in formulations discussed in the viral section. (NCR-Columbia, MO).

3 Weed biotic agents except pathogens

a Select appropriate target weeds on the basis of the following criteria: (SR-Temple, TX; Stoneville, MS; Gainesville, FL; Ft. Lauderdale, FL).

i Measure the distribution of the weed in the U.S.; develop remote sensing and survey methods.

ii Calculate the potential spread of the weed in the U.S. based on its physical requirements such as temperature, rainfall, and soil.

iii Measure damage caused by the weed within the infested area to crop and livestock production, natural resources, or public health.

iv Measure the beneficial value of the weed such as for ornamentals, wildlife food and shelter, honey production, place in the food chain of other organisms, erosion control, etc.

v Compare the efficiency of the various possible methods of control such as introduction of foreign organisms, augmentation of native organisms, chemical or mechanical controls, or various combinations of these.

vi Make a cost-benefit analysis to determine the most efficient method of control to adopt.

b Estimate the impact of the various controlling agents on weed populations to find the most effective point at which to direct augmentative efforts. (SR-Temple, TX; Stoneville, MS; Gainesville, FL; Ft. Lauderdale, FL).

i Measure growth and reproduction of the weed in various areas under natural and controlled conditions.

ii Compare weed growth and reproduction under the influence of various controlling agents, present singly or in complexes, and without controlling agents.

iii Determine the part of the weed attacked by the various agents, and their effect on photosynthesis, water and nutrient transport, food reserves, reproduction, and overwintering.

c Develop the most effective methods of augmenting the weed's biotic suppressants: (SR-Temple, TX; Stoneville, MS; Gainesville, FL; Ft. Lauderdale, FL).

i Increasing the number of suppressants by distribution from naturally occurring areas of surplus.

ii Developing methods of mass rearing suppressants in the laboratory on host plants, or on artificial diet in sufficient numbers, and at a low enough cost to provide control.

iii Reducing the mortality of suppressants by parasites, predators, or pathogens in the field.

d Develop methods of manipulating the agroecosystem to increase the control provided by biotic suppressants such as: (SR-Temple, TX; Stoneville, MS; Gainesville, FL; Ft. Lauderdale, FL).

i Increasing the competition from other vegetation.

ii Integrating chemical and mechanical controls with biological controls so that weeds are controlled at all times of the year and in all ecological situations where they cause damage.

iii Developing methods such as fertilization or application of chemicals to increase the acceptability or nutritive value of the host plant to the suppressants, or to otherwise increase their effectiveness.

e Develop methods of conserving suppressant populations in a field such as: (SR-Temple, TX; Stoneville, MS; Gainesville, FL; Ft. Lauderdale, FL).

i Timing of insecticide application aimed at insect enemies of crops.

ii Providing requisites in short supply such as alternate hosts, food plants, or shelter.

iii Modifying planting dates, crop rotations, or other cultural modifications.

f Assess the degree of control obtained and evaluate monetary savings, increased environmental quality, increased recreational uses, reduced public health hazards, etc., and make a cost-benefit analysis derived from the control. (SR-Temple, TX; Stoneville, MS; Gainesville, FL; Ft. Lauderdale, FL).

4 Weed pathogens

a Increase the survey and identification effort of native weed pathogens; select for study, genera with high potential as weed-control agents. (WR-Albany, CA; NER-Frederick, MD; NCR-St. Paul, MN; SR-Stoneville, MS; Stuttgart, AR).

b Increase research efforts on native weed pathogens; prime targets for research include Colletotrichum gloeosporioides f. sp. aeschynomene of northern jointvetch, Cercospora rodmanii of waterhyacinth (Eichornia crassipes), Phytophthora citrophthora of strangler vine (milkweed vine) (Morrenia odorata), Colletotrichum malvarum of prickly sida (Sida spinosa) and other promising weed pathogens discovered in the surveys. (WR-Albany, CA; SR-Stoneville, MS; Stuttgart, AR).

c Expand research on biology of native weed pathogens that show promise for control of weeds. Study the host-pathogen relationships and interactions, life cycles of the pathogens, specificity, culture, growth requirements, mass production of inoculum, and other relationships. (SR-Stuttgart, AR; Stoneville, MS).

d Develop and improve cooperative effort with EPA to develop guidelines for registering pathogens for control of weeds. (WR-Albany, CA; NER-Frederick, MD; NCR-St. Paul, MN; SR-Stoneville, MS; Stuttgart, AR).

e Increase cooperative research efforts with private fermentation industry to register new weed pathogen bioagents. (SR-Stuttgart, AR).

f Integrate technology of weed control with pathogens into weed-control systems that combine herbicides, cultural and mechanical practices, and pathogens. (SR-Stuttgart, AR; Stoneville, MS).

g Computerize world data on plant pathogens and their hosts. (None).

5 Antagonists of plant pathogens

a Seek soils locally, nationally, and internationally wherein little or no disease occurs in spite of the introduction or existence of pathogen, susceptible plants, and disease favorable environment; separate biological from nonbiological factors responsible for the suppressiveness; determine the biological factors by selective treatments such as heat, water potential and/or chemicals; determine inoculum-disease response relationships in suppressive soils and conditions necessary for expression of suppressiveness; isolate candidate antagonists and evaluate their potential to lyse, parasitize or competitively exclude the pathogen from host plant tissue in soil; study the nutrition, ecology and biochemical capabilities of promising candidate antagonists in order to devise means of using them as biocontrol agents; apply antagonists to field plots and determine their effectiveness in reducing crop loss through disease. (Presently under study by Western Regional Coordinating Committee No. 12; ARS has cooperating projects from WR-Pullman and Prosser, WA).

b Widen the search for mutants, strains, or other close relatives of pathogens and test these as potential stimulants of host resistance (Corvallis, Prosser, Pullman) or hypovirulent or avirulent types with capacity to destroy or weaken its pathogenic relative (ARS, none; SAES, some). For example, in Australia a newly discovered avirulent mutant of the crown gall bacterium produces a bactericin that kills the pathogenic strain and prevents crown gall. In Connecticut, a hypovirulent strain of the chestnut blight fungus transfers its hypovirulence to the pathogen and controls blight. Tests with candidate isolates should be made on different genotypes of a given host species and should be tested in advance of, concurrent with, and following attempted invasion by the target pathogen.

c Test mild or subtle fumigation or other pesticide or soil treatments and monitor for resultant pathogen population decline over weeks, months, or years (WR-Pullman, WA; NER-Beltsville, MD, 20270; SAES); compare tillage systems, amendments, or other methods of exposing propagules to the weakening influence of desiccation, UV-radiation, oxygen deficiency, ethylene, aldehydes, or other predisposing stress treatments (WR-Pullman, WA; Corvallis, OR, 20270; SAES); test irrigation, fertilizers, or residue management treatments to shift the soil environment to the disadvantage of pathogens in host residue, thereby weakening their position and encouraging their replacement in plant tissues by saprophytes (Forest Service). Such experiments depend on new and improved methods of monitoring populations of target pathogens.

d Widen the search for antibiotic, hyperparasitic, or competitive microorganisms and test these as stem injections (Wooster, OH), foliar or floral sprays in cell suspension to protect leaves or flower parts (SR-Raleigh, NC; SAES), or as seed dressings to protect seeds, or to establish the antagonists in the root zone (SAES). Sites that presently show little or no disease in spite of apparently favorable conditions and ample opportunity for disease should be first-choice situations to seek candidate antagonists.

D Consequences of Visualized Technology.

1 Parasites and predators

a Lower costs of agricultural production.

b Increase agricultural production.

c Increase the effectiveness of introduced and native parasites and predators by periodic mass releases of beneficial insects, reduced insecticide usage, use of behavioral chemicals and artificial foods.

d Reduce environmental pollution and hazards to man due to pesticide residues in soil, water, and air.

e Decrease the amount of energy used in manufacturing insecticides.

f Some of the insecticide manufacturers may suffer economic loss equivalent to net reduction in insecticide usage, but this may be offset partially by increased proceeds due to production of behavioral chemicals and artificial foods for parasites and predators.

g Create new industries for production of insects to be used in augmentation programs and new distribution systems for beneficial insects.

h Decrease the effort required to determine the feasibility of parasite/predator augmentation and/or conservation programs through use of computer simulations.

i Possibly increase undesirable predator/predator or parasite/parasite interactions as a result of augmentation and conservation programs.

j Reduce the cost of augmentation of beneficial insects and nematodes by lowering the cost of rearing them.

2 Insect pathogens

a Reduce the need for toxic insecticides in forest and crop insect control.

b Reduce the need for petroleum-derived insecticides, thus contributing to the alleviation of the energy problem.

c Provide safe insecticides for use on food crops and stored products.

d Reduce the cost of insecticidal applications, particularly in view of the rising cost of chemical insecticides, and thus reduce the costs of producing food, fiber, and forest products.

e Increase production of food, fiber and forest crops by improved control of pests.

f Increase income of food, fiber, and forest producers.

g Decrease environmental pollution by reduction of chemical insecticide applications.

h Provide a safe and acceptable means of insect control in residential and recreational areas.

i Allow treatment of susceptible pests without danger to beneficial insects (bees, predators, and parasites).

j Reduce income of chemical insecticide producers.

k Develop a new industry for production and utilization of entomopathogens and entomopathogenic agents in insect control.

l Utilize waste products (nitrogenous and carbohydrate) for production of insecticidal material rather than the more expensive and rapidly depleting chemicals currently used in the production of insecticides.

m Offer means of protecting against insect pests by introducing diseases into the natural population that can reduce or eliminate the need for chemical treatments.

n Increase the need for skilled pest control operators who can dictate the timing of application and the usage of these limited-spectrum agents.

3 Weed biotic control agents except pathogens

a Allow the selection of the most appropriate target weeds without loss of research effort on unpromising candidates.

b Allow the selection of the most efficient means or combinations of control methods.

c Reduce the cost of weed control and thus of food production.

d Increase the quality of water, rangeland, and wilderness area resources.

e Increase the recreational value of parks, waterways, and natural areas.

f Reduce public health hazards from poisonous or allergy-producing plants.

g Develop the technology for industry to produce organisms for weed control.

h Reduce the usage of herbicides.

i Reduce the possibilities of plant resistance to herbicides.

j Allow replacement of weeds by more desirable plants.

k Reduce abundance of weeds not presently amenable to control with chemical or mechanical means.

l Increase agricultural production by controlling weeds that clog irrigation and drainage canals.

m Remove selected unwanted plant species from mixed communities without detrimental effect on the other species.

n Remove weeds from areas difficult to reach by other methods.

o Increase ability to control weeds with natural enemies in specific areas without killing the plants in areas where they are considered of value.

p Possible replacement of one weed with another more obnoxious weed.

q Possible damage to plants valuable as ornamentals, wildlife food and shelter, honey production, etc.

r Possible increased pollution of streams by removing weeds that utilize the excess nutrients.

s Possible increase of soil erosion by removal of plant cover.

4 Weed pathogens

a Control of weeds resistant to chemical techniques.

b Control of weeds on marginal land where economics are unfavorable for herbicides.

c Reduced crop injury.

d Improved crop yields and quality.

e Reduced weed control costs.

f Conservation of water in dry land regions.

g Reduced use of chemical herbicides.

h Reduced chemicals in the air, water, soil, and food.

i Lowered income of chemical herbicide industry.

j Increased income of fermentation industry.

k Increased private interests in development of new mycoherbicides.

l Expanded availability of pathogen-host information to scientists.

5 Antagonists of plant pathogens

a Reduce or eliminate the need for fungicides, bacteriocides, and nematocides.

b Provide a means to control certain wilt and root rot diseases where presently no host resistance, cultural, or other control exists; control of such soilborne pathogens would greatly improve productivity of the host crop.

c Reestablish a soil biological balance involving complex and more stable communities more similar to that of the original undisturbed land before agriculture, but without sacrifice of food, feed, or fiber production.

d Millions of acres of western irrigated lands no longer fully productive because of heavy infestations with soilborne pathogens, particularly Verticillium, Fusarium, Rhizoctonia, and nematodes could be restored to their original productivity if a good biocontrol of these pathogens were developed.

e Certain processing crops, e.g., fresh peas, or certain tomato varieties preferred by the industry and the customer, but presently replaced by less palatable varieties with necessary resistance to Fusarium wilt could again be grown if a good biocontrol of Fusarium wilt were developed.

f Where avirulent strains related to pathogens are used the risk exists that reverse mutations, or synergism with the pathogen on other unexpected host crop could contribute to increased disease in some situations.

E Potential Benefits

1 Parasites and predators. The technology for augmentation and conservation of parasites and predators is so recent that potential benefits are difficult to document. However, there are some examples of savings that may accrue when parasites and predators are conserved, and indicate potential when augmentation is practiced.

Spiders and entomophagous insects, particularly ants, play a major role in control of the sugarcane borer in sugarcane in Louisiana. When these beneficials are eliminated by applying selected organochlorine compounds, the number of insecticide applications required for sugarcane borer control is doubled. Another example of selective use of chemical control is the "reproductive-diapause" method for controlling boll weevils. Overwintering boll weevil populations are reduced during the late season and fall resulting in a 40 to 50% reduction in chemical applications for boll weevil control the following year, thereby increasing the effectiveness of natural enemies controlling bollworms, tobacco budworms, and the banded wing whitefly.

Mass production and use of predators and/or parasites in augmentation programs in lieu of chemical control procedures may be effective at costs less than 1/2 that of insecticides. However, effective insecticides may not be available long due to development of resistance in many pests. Thus, this technology is needed even if initial costs exceed costs of current chemical control procedures. Some recent examples using the augmentation concepts include beneficials such as Chrysopa carnea, Trichogramma sp., Lixophaga diatraeae, and Spalangia endius. Trichogramma sp. was reared and released at the rate of 300,000/acre for $8.40 and recent results using a different host indicate that 60,000 parasites/acre may control Heliothis species. Projected costs indicate that the sugarcane borer in Florida can be controlled with L. diatraeae for about $8.00 to $12.00/acre. Further, sustained releases of S. endius

completely suppressed a housefly population at a cost slightly less than that for pesticides. This approach is pest specific, does not adversely affect environmental quality, and eliminates many of the problems associated with pesticide usage.

A unique method of control of phytophagous mites that resulted in less cost involved simply letting vineyards remain weedy. Small numbers of phytophagous mites moving from weeds to grapevines served as an alternate prey for a predaceous phytoseiid mite thereby producing a more stable population and reduced miticide usage. Alterations of other agroecosystems could produce similar benefits.

Costs for supplementary foods are currently not competitive with costs for conventional pesticide control methods. However, the pest control approach of applying supplementary foods on crops is in its infancy and shows considerable promise for use in monoculture crops.

When one behavioral chemical was applied as a foliar application to plants, rates of parasitization of host eggs by Trichogramma sp. were increased by improving the retention and efficacy of search by the parasite. The effective dosage ranged from 100 to 1000 mg of synthetic chemical per acre and remained effective for at least 5 days. These chemicals could be used alone or in combination with an augmentation program.

The effective utilization of native parasites and predators should save $500,000 for every million dollars currently spent on insecticides. Likewise, the amount of energy expended for the current level of insecticide production should be decreased by 50% in ten years. Assuming that there will be no counterproductive results from increasing indigenous beneficial insect usage, environmental pollution should be reduced 50% over the next decade. The research effort required to determine the feasibility of individual augmentation and conservation programs could be reduced 25% over the next ten years. This will be a net result of efforts expended to gather input data for computer simulations of the Visualized Technology.

2 Insect pathogens. Those entomopathogens that infect insects and those that produce harmless toxins (such as the δ-endotoxin produced by B. thuringiensis) offer, almost by definition, the benefit of safety -- they will have before they are released, Exemptions from the Requirements for Tolerance from the EPA. They will not pollute the environment since they are naturally present in the environment; and they will not harm beneficial insects. Because these microbial insecticides have the potential to replace large quantities of chemicals it can be considered a benefit every time one replaces a chemical. Table 1 shows the potential effects of the development of satisfactory formulations of some of the entomopathogens being studied today. The first four crops in the table (vegetables, corn, cotton, and tobacco) are presumed to be treated with either improved formulations of the BT δ-endotoxin, or with viruses -- in the last crop, most likely with the alfalfa looper virus or the Heliothis virus. It is presumed that Entomophthora thaxteriana can successfully attack the green peach aphid on potatoes and that Nosema locustae, or a related organism effectively controls the grasshopper and persists in the environment to hold populations of the grasshopper to sub-

economic levels. All of these goals are in sight, given the adequate funding and staffing needed for the research, and, as the table shows, it is possible to envisage 36 million pounds of chemical insecticides being replaced by microbials, and with the market for microbials approaching $330 million.

Table 2 shows a potential benefit of more immediate promise. It has been shown that the B. thuringiensis -δ-endotoxin can effectively protect stored agricultural products from the Indian meal moth and the almond moth. Efforts are underway by ARS scientists to clear the product for use in stored products. Unless unexpected obstacles arise, the necessary clearance and labeling should be obtained in the next year or two. Present chemicals and treatment procedures do not work well, and there is a good chance that the δ-endotoxin will become the treatment of choice to protect these materials. The annual requirements for BT would, in that case, be greater than 1 million pounds with a dollar value of over $10 million.

Improvements in the BT formulations, or successful development of some of the viruses against forest insects (in particular the gypsy moth and the tussock moth) could lead to widespread usage of microbials in forest protection, a very large market for these microbials. No effort has been made to predict these markets, since this is an area primarily the responsibility of the Forest Service.

Development of a commercially feasible procedure for the production of Bacillus popilliae could lead to successful control of an insect currently causing over $25 million/year in damage. Certainly, use of B. popilliae would reduce this damage caused by the Japanese beetle, perhaps by as much as 50-70%, for an annual saving of $13-18 million.

It is impossible to make any serious dollar prediction about the value of microbes in the control of mosquitoes. But when one considers the vast amount of money spent each year in mosquito control, one must realize that even if only 10-20% of this money were saved by introducing effective diseases into the mosquito population, the dollar contribution of the microbial would be great.

The search for microbial toxins other than the δ-endotoxin should lead to the development of microbial insecticides with low toxicity and narrow spectra of activity. In contrast to the previously discussed entomopathogens, these toxins will be toxic to some extent, although less so than chemicals, and they will not be normally present in the environment. Thus, they will have to be introduced into crop protection more in the manner of chemicals than in the manner of the other microbials. They will still have the advantage of safety and minimal disturbance of the environment. Because these products have narrow-spectra, they can be selected to minimize any danger to beneficial insects. Since research on these microbial toxins has just begun, it is impossible to put any dollar value on the benefits that will accrue, but they should be high. The toxins should be able to compete price-wise with chemicals, and, in fact, since the cost of raw materials for the chemical insecticides is rising rapidly, it can be expected that eventually the biological may be cheaper than the chemical. These microbial insecticides should have particular value in protection of such crops as cotton, where chemicals are

Table 1.--Possible Annual Retail Value of Crop Protection by Microbial Agents by 1986 1/

Crop	Annual Acreage Grown X1000	Acreage Treated with Insecticide X1000	Pounds Insecticide Used X1000	Possible Pounds Replaced by Microbial Agents X1000	Dollar Value 2/ X1000
Vegetables	3,333	1,866	8,494	3,000	27,000
Corn	74,055	25,919	27,315	5,000	45,000
Cotton 3/	12,355	7,540	73,365	25,000	225,000
Tobacco	839	646	4,143	2,000	18,000
Potatoes 4/	1,432	1,102	2,889	1,400	13,000
Rangeland	270,000 5/	735	333	6/	2,000 6/
			TOTAL:	36,400	330,000

1/ Estimates based on the production of crops and use of insecticides in 1971; Agric. Econ. Rep. 252 (1974), 268 (1975).

2/ Dollar value computed by assuming the retail value of a microbial insecticide equivalent to 1 pound of a chemical insecticide is $9.00. This is reasonable by current costs.

3/ Does not include treatments for insects other than *Heliothis* spp.; includes viruses.

4/ Treatment for green peach aphid only; *Entomophthora thaxteriana*.

5/ Estimated total pastureland in northern plains and mountain states.

6/ For control of grasshoppers only; assuming less than 1/10 of land infested with grasshoppers is now treated, and that successful development of *Nosema locustae* would permit treating all land infested, the dollar value represents estimated annual benefit rather than the cost of the chemicals replaced.

Table 2.--Estimated Annual Use and Retail Value of *Bacillus thuringiensis* (BT) Used in Protection of Stored Agricultural Products by 1986.

Product	Annual Storage X1000	Quantity Treated X1000	Pounds BT Required X1000	Retail Dollar Value X1000
	BUSHELS	BUSHELS		
Wheat	438,000	110,000	82.1	739
Corn	3,200,000	800,000	600.	5,400
Sorghum	187,000	46,800	35.1	316
	TONS	TONS		
Rice	440	110	46.2	416
Peanuts	1,750	438	184.	1,650
Raisins	191	144	60.2	542
Prunes	157	118	49.5	446
Almonds	140	105	44.1	397
Walnuts	137	103	43.2	389
		TOTAL:	1,140.	10,300.

becoming less effective because of the increasing resistance of the insects to the chemicals, and should easily expect multimillion dollar markets.

3 Weed biotic control agents except pathogens. The potential benefits of augmentation, manipulation, and conservation practices is such a new area of research that few examples of the benefits from such programs are available. The potential benefits are more evident as reducing the upset of the environment and improved control of weeds that are difficult to control with chemical or mechanical means. Monetary savings will probably be comparable to present costs of chemical controls, since most augmentation methods require a constant input of energy or effort by man.

The present program in Mississippi to control purple nutsedge (Cyprus rotundus) by mass release of larvae of the moth Bactra offers possible savings because satisfactory control is not now possible by other means. Present cost of marginally effective control by chemicals is \$6.00/A, regardless of the density of the weed population. Present objectives are to mass-produce Bactra adults to give control of maximum populations of nutsedge (ca. 1,000,000 shoots/A) at a cost of \$100/A. Since the number of Bactra required depends on the number of weed shoots to be controlled, light Cyperus infestations will require fewer Bactra and would be competitive with present control costs. However, to be effective at high weed densities the cost per adult obviously must be reduced. Bactra has the potential for providing better control than the present chemicals, which would result in greater crop yields.

Great potential benefits may be realized in control of several weeds that cannot be controlled by introduction of foreign organisms because of beneficial uses of the plant in some locations, or because the close phylogenetic relationship of beneficial plants makes introduction too risky.

Effective control agents may not exist in foreign countries, or may not be introduced because they are not sufficiently host specific. For these weeds, the only alternative for biological control is augmentation of native suppressants. Native weeds of major importance that may fall into this category are mesquite (Prosopis spp.) with the twig girdler, Oncideres rhodostica, with the cutworm, Melipotis indomita; sagebrush (Artemisia spp) with the defoliator, Aroga websteri; ragweed (Ambrosia spp.) with the leaf feeder, Farachida candefacta; broomweed (Gutierrezia spp.), and stem boring cerambicids; and creosotebush (Larrea sp.) with a phasmid.

4 Weed pathogens. Estimated losses from specific weeds and potential benefits from use of native mycoherbicide bioagents follow:

Weed	Crop	Acres infested 1/ (thousands)	Losses 2/ %		Losses 2/ $ Million	Benefits from use of bioagents 3/ %	Benefits from use of bioagents 3/ $ Million
Northern	Rice	165	6		4.2		
jointvetch	Soybeans	330	3		1.5		
				TOTAL	5.7	50	2.8
Prickly	Cotton	233	5		2.6		
sida	Soybeans	405	5		2.5		
				TOTAL	5.1	5	.3

1/ Data obtained from extent and cost of weed control with herbicides and an evaluation of important weeds, 1968. ARS-H-1, 1972; Research Report of the Southern Weed Science Soc. 1974.

2/ Percent loss values based on research reports. Dollar losses calculated from acres infested, average yield of crop, average price of crop, and assigned percent loss values.

3/ Percent benefit values based on research for northern jointvetch and prickly sida.

Northern jointvetch infests an estimated 15% of the rice acreage, or 165,000 acres in Arkansas, Mississippi, and northern Louisiana. If this weed were not controlled yield losses are estimated at 4% and quality losses at 2%. Based on 1975 production and prices, losses caused by northern jointvetch totaled $4.2 million. Northern jointvetch is presently controlled in rice by phenoxy herbicides, chiefly 2,4,5-T. This herbicide frequently cannot be used because of possible damage to nearby susceptible crops, e.g., soybeans and cotton, or injury to the rice crop.

It is estimated that 330,000 acres of soybeans in the Arkansas-Mississippi-Louisiana area are infested with northern jointvetch that causes 2% losses in yield and 1% losses in quality for a total loss of $1.5 million. Field experience obtained from a pilot testing program indicates that the northern jointvetch fungus gives 95% or more control in rice and 50 to 75% control in soybeans. Furthermore, if the fungus controls northern jointvetch in rice fields, it may successfully control weed plants that infest soybeans planted after rice. If this fungus can be developed for commercial use, it is believed that losses prevented by use of the northern jointvetch bioagent would be 50% of those that occur in rice and soybeans, or a savings of $2.9 million annually.

The endemic fungus that attacks prickly sida has given 80-90% control in field experiments. Prickly sida is an increasing problem in soybeans and cotton grown in the South where in 1974 it was rated among the top 10 most common weeds in cotton in 8 States (Alabama, Arkansas, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee), and in soybeans in 5 States (Alabama, Louisiana, Mississippi, South Carolina, Tennessee). Because this weed is tolerant to many of the herbicides used in cotton and soybean weed-control programs, it is increasing as a weed problem. The successful commercial development of the prickly sida fungus could reduce losses from this weed by an estimated $300,000 annually; benefits would increase as usage increased above the 5% acreage level.

Strangler vine infests 25% of the citrus in Florida. Successful development of Phytophthora citrophthora could reduce infestations to 5 to 10% of the trees during the next 10 years. The fungus combined with herbicides and cultural practices could completely eliminate losses in citrus caused by strangler vine.

Waterhyacinth, which infests 70, 40, and 20% of the aquatic areas in Florida, Louisiana, and Georgia, respectively, interferes with navigation, irrigation, and recreational uses of water. In Florida alone an estimated 300,000 acres are infested with this weed; $15 million are expended annually for its control. Cercospora rodmanii combined with other pathogens, e.g., Acremonium zonatum, and Helminthosporium stenospilum, with weed-feeding insects and fish and with herbicides could significantly reduce losses from waterhyacinth and expenditures for control.

Complexes of weed pathogens and insects reduce the vigor and growth of waterhyacinth to make it more susceptible to control with herbicides and weed-eating fish. In the next 10 years research could develop technology to eliminate losses caused by waterhyacinth.

5 Antagonists of plant pathogens

a Control of Verticillium wilt of potatoes could increase potato yields in the irrigated west by 50 cwt per acre while eliminating the current practice of soil fumigation which costs $100 per acre.

b Control of Fusarium wilts of peas and tomatoes, the two main vegetable crops affected in the U.S., could increase yields by 25-50% in fields presently affected while decreasing current massive programs in the public and private sectors on breeding for resistance, and allow return of certain preferred varieties.

c Development of soils antagonistic to cortical rotting fungi (soils microbiologically suppressive to Rhizoctonia, Fusarium, Pythium, or Phytophthora) would benefit the avocado, cotton, apple, pear, strawberry, alfalfa, wheat, potato, tobacco, pea, bean, soybean, corn, and other industries since annual losses in each of these crops by one or more of the above pathogens is a conservative 5%.

d Control of the chestnut blight fungus by hypovirulent relatives of the pathogen could restore stands of this prized hardwood tree, now nearly extinct in the U.S. Similarly, control of the Dutch elm disease by an antagonist injected into the trunk (Wooster, OH), could save this magnificent tree species from doom in the Midwest.

F Research Effort

Current Level

1 Parasites and predators. There are currently about 44 SY's in ARS whose research objectives relate to TO III.2. Of the 44 SY's listed only about 10 are, or will be working under NRP 20260, and the remainder are divided among other NRP's (20220, 20230, 20240, 20250, 20480, and 20620).

About 1/2 (22.45) of the SY's are concentrated in the area for development of rearing programs and related research required for development of augmentation programs. However, little work (about 0.5 sy) is directed toward strain selection and development of quality control criteria. About 1/4 (10.35 SY's) are conducting research that relates to Research Approach (h) and could be used in developing field models for host-parasite or predator-prey interactions. Another related area, alteration of agroecosystems to the entomophage's advantage, contains only about 1.0 SY. One of the more promising new areas, the identification and use of behavioral chemicals, has less than 5 (4.7) SY's devoted to it and only 1 SY is devoted toward research on development of artificial foods.

Current insect control practices are most dependent on research conducted in the past that related to development of maximum economic thresholds, minimum dosage rates of chemicals, use of chemicals effective against pest species, but least harmful to beneficials, agroecosystems alterations, and information that could be used in a modeling approach. However, only about 1/4 (11.85) of the SY's are devoted to research of this nature. Clearly this indicates a need for strengthening these critical areas.

The use of plant varieties in which insect resistance has been incorporated is evolving as a major component in insect pest management programs. However, little attention is apparently given to the impact that new plant varieties may have on natural enemy complexes within agroecosystems. An ecologist should be located with breeding laboratories to consider this aspect.

Expanded Level

At least 1 SY should be devoted to each major crop agroecosystem area whose primary responsibility would be to reduce the effects that pesticide practices have on natural enemies. Agroecosystems that should be considered are as follows: Cotton, tobacco, small grain, corn, soybeans, alfalfa, sugarcane, vegetables, fruit, and turf grasses. Total SY's = ca. 8.

At least 1 SY should be associated with each major plant breeding program to evaluate the impact of new plant varieties on natural enemy populations. Agroecosystems that should be considered are as follows: Cotton, tobacco, small grain (wheat), corn, soybeans, alfalfa, and sugarcane. Total SY's = ca. 7.

The development of the augmentation concept is generally dependent on a mass rearing program, which presently includes the host and entomophage. Thus, at least 2 ecologists (field evaluations) and an insect rearing specialist are required. Methods for measuring and maintaining the quality of the laboratory-reared beneficial would probably require the full-time attention of an insect behaviorist. Other individuals needed to support this program would include an insect nutritionist (0.5 SY), an economist (0.5 SY), and an agricultural engineer (1.0 SY) for development of mechanized rearing methods and distribution systems. In addition, services of an insect pathologist (0.5 SY) and a systems analyst (0.5 SY) are also needed. The successful development of the augmentation concept in selected areas obviously requires the team approach. It is highly unlikely that 2 to 3 individuals can successfully develop all facets of such a program. Thus, programs of this nature require about 7 SY's each located at about 3 ARS facilities. Total = 21 SY's.

The effort toward identification and study of behavioral chemicals should be doubled (total = 9 SY's). Further, more effort needs to be directed toward development of economical supplementary foods. Development of this technology will require coordination between a biochemist/nutritionist and an entomologist and work should be conducted at 2 locations (total = 4 SY's).

A major portion of the cost for mass production of beneficial insects is in rearing of host insects. Additionally, the production system is complicated and chance of disease outbreaks is high. The development of artificial diets could reduce production costs, simplify the production system, and reduce the probability of a program hiatus due to a disease outbreak. Accomplishment of this technology will require an interdisciplinary approach including a research entomologist (1 SY), a biochemist with a nutrition specialty (1 SY), and an agricultural engineer (0.3 SY) located at each of 3 laboratories (total = 6.9 SY).

The development of host-parasite or predator-prey models and associated research components often can be accomplished in conjunction with augmentation programs. However, there will be a need to conduct studies of this nature at other locations. Effort in this research area should be increased by about 10 SY's. total = 10 SY's.

The SY requirements given above would be included in NRPs 20220, 20230, 20240, 20250, 20480 and 20620 as well as 20260; only 10 SY's would be involved directly in NRP 20260.

	Year	20260	Current Support SY's NRP's	Gross Dollars	Expanded Effort 1/ SY's (ARS Only)	
ARS	FY76	2.0		331,851	10.0	
SAES					--	--
Other					--	--
Total						

	Current Support	Expanded Effort
Years required for ARS to achieve the Visualized Techonolgy	10	5

1/ Includes base and additional SY

2 Insect Pathogens

a Current Levels. At the present time, there are 34.3 SY's being expended in all NRP's on research on insect pathogens. Only 17 SY's are or will be in NRP 20260, as follows: Beltsville - 11, Columbia - 3, Peoria - 2, Brownsville - 1.

b Expanded Level. If all the research approaches were to be undertaken simultaneously, a very large increase in effort would be required. However, appreciable additional effort could be allocated as follows:

Research Approach	SY's
Bacteria	3.0
Fungi	2.0
Actinomycetes	1.0
Protozoa	2.0
Viruses	8.0
	16.0

Additional Facilities, $300,000. Work with fungi and protozoa.

	Year	Current Support SY's	Gross Dollars	Expanded Effort 1/ SY's (ARS Only)
ARS	FY76	14	1,144,482	30
SAES				
Other				
Total				30

	Current Support	Expanded Effort
Years required for ARS to achieve the Visualized Technology	10	6

1/ Includes base and additional SY.

3 Weed biotic control agents except pathogens. Techniques of augmentation, manipulation, and conservation may also be used to increase the effectiveness of introduced foreign organisms as well as native organisms. Therefore, the research effort under Technological Objective #1 will in some cases supplement the effort in Technological Objective #2 and vice versa.

		Current Support		Expanded Effort 1/
	Year	SY's	Gross Dollars	SY's (ARS Only)
ARS	FY76	1	101,460	4
SAES				--
Other				--
Total				

Years required for ARS to achieve the Visualized Technology	10	5

1/ Includes base and additional SY.

4 Weed pathogens

		Current Support		Expanded Effort 1/
	Year	SY's	Gross Dollars	SY's (ARS Only)
ARS	FY76	1.0	60,000	5.0
SAES	FY76	3.0 2/	180,000	
Other	-	-	--	-
Total		4.0	240,000	5.0

Years required for ARS to achieve the Visualized Technology	10	5

1/ Includes base and additional SY
2/ At least 1.0 SY is short term (Ends FY77).

5 Antagonists of plant pathogens

		Current Support 1/		Expanded Effort 5/
	Year	SY's	Gross Dollars	SY's (ARS Only)
ARS	1975-76	0		4.0
SAES	1975-76	15.0 2/		
Forest Service	1975-76	1.5 3/		
Industry	1975-76	1.5 4/		
Total		18.0		

Years required for ARS to achieve the Visualized Technology	?	10

1/ Note: Of some 2,500 members listed in the American Phytopathological Society 1974 membership list, 191 list themselves as working on biological control of plant pathogens. Another 15-20 should be added to allow for a net gain since 1974. Of the current total, an estimated

16 work for ARS, 8 are from outside the U.S., 6 work for the Forest Service, 6 work for private industry, and the remaining 150-160 work for the SAES. Not one of these people can be identified with full-time work on biological control, but all devote at least some effort to this approach.

2/ Based on an average of 10% effort from each of 150 scientists.

3/ Based on 25% effort from each of 6 scientists.

4/ Based on 25% effort from each of 6 scientists.

5/ Includes base and additional SY.

The support needed in order of priority is suggested as follows:

1. Additional support for existing scientists and programs, but identified as support for biocontrol.

2. Establishment of a national center with at least 4 SY's for basic and applied research on biocontrol of plant pathogens. Such a center would be best located in the West where soilborne pathogens are the most serious and where opportunities for reaching the Visualized Technology are greatest.

III.3 New and improved principles and practices of insect and mite identification.

A Current Technology. Accurate identification is the critical first step and the final integrating framework for much research involving organisms in the agricultural, biological, and health sciences. Identification of pest and beneficial insects and mites is the keystone of pest control. This is particularly true in biological control where it is often essential to be able to differentiate between structurally very similar species.

The broadly based research and service activities of this TO are specifically designed to support current and future needs of the following NRPs:

Plant and Entomological Sciences

NRP 20180 Bees-pollination and honey production
20220 Insect control - horticultural crops
20230 Insect control - cotton and tobacco
20240 Insect control - field crops
20250 Insect control - basic/non-commodity
20260 Biological Agents for Pest Control (TO I and II)
20270 Disease and nematode control - crops
20280 Weed control
Special Research Program: Production and control of narcotic plants

Livestock and Veterinary Sciences

20480 Livestock insect control

Marketing, Nutrition, and Engineering Sciences

20620 Insect control in marketing
20850 Control of insects affecting man

International Programs Division

Special foreign currency supported research
Tropical and subtropical agricultural research and training

Currently, about one million species of insects alone have been described, primarily on structural characteristics. Estimates have placed the total number of insects and mites, including those yet to be discovered and described, at 3-10 million species (Sabrosky, Yearbook of Agriculture, 1952; Moore, Systematic Zoology, March, 1976). These are being described by taxonomists throughout the world at a rate of about 8,000 new species per year. At present only about 40% of the species of the major orders of the North American insect and mite fauna have been described. Furthermore,

a 1976 survey in the Systematic Entomology Laboratory, USDA, shows that the limited number of highly competent taxonomists with the required but scarce literature and largest reference-specimen resources can positively identify only about 41,000 of the 104,000 described North American species.

A thorough and accurate classification of all insects and mites of the world is impossible, even with major increases in support for systematics. Probably no more than 50% of the total insects and mites of the world can be described and classified over the next 100 years with present levels of support. Also, it is impossible to predict closely which species will need to be classified and identified. Thus, research and identification capability in systematics needs to be as broad and as flexible as possible. Flexibility is limited by the high degree of specialization necessary when each research taxonomist must work with huge numbers of taxa. Thus, a certain "critical mass" of taxonomists is required, a number of scientists below which authoritative research and identification cannot be produced.

Almost all research and identification of insects and mites in ARS is conducted by the Systematic Entomology Laboratory (SEL), a part of the Insect Identification and Beneficial Insect Introduction Institute, Beltsville Agricultural Research Center. The SEL, with 29 research entomologists, is the principal center for taxonomic research and identification of insects in the western hemisphere and is the second largest of three major world centers. (The Biosystematics Research Institute, Agriculture Canada and the British Museum - Commonwealth Institute of Entomology being the other two).

Very little taxonomic research on insects and mites is being conducted in other ARS laboratories. Only two CRIS projects outside SEL include taxonomic research (Nielson, Tucson, AZ, "Bioecology of Alfalfa Insects and Biosystematics of Leafhoppers" WRU No. 5502-10920-002 and Parker, Bee Biology and Systematics Laboratory, Logan, UT "Pollination Insects Research" WRU No. 5702-15560 (NRP-20180). Taxonomic research is conducted to a minor extent by: DeLoach, Temple, TX, weed-feeding insects; Puttler, Columbia, MO, parasitic wasps; Chapman, Lake Charles, LA, mosquitoes; Vogt, Stoneville, MS, weed-feeding beetles; Bluem and Aga, TX, dung beetles. A moderate amount of taxonomic work has been conducted over the years by means of Cooperative Agreements funded by SEL.

Taxonomic research and related activities are conducted in the SEL along the following lines. In practice there is no sharp distinction between morphological and biosystematic research--certain organisms require emphasis on one approach, other organisms require emphasis on the other approach.

1 Morphological Taxonomy. This is research based on anatomical features of insects to allow species to be identified by direct examination of specimens. Recognition of variation within and among populations is a major part of the activity in morphological classification. Morphological taxonomic research has been pursued for many years as the most direct and generally valid approach toward solution of identification and classification problems.

2 Biosystematics. Biosystematics comprises research leading to the detection of differences between populations based on behavioral and physiological characteristics. Recently, it has become increasingly obvious that morphological taxonomy may fail to achieve the degree of precision required to differentiate between many of the insects which affect man's welfare as crop pests and vectors of disease, or which may be useful as natural enemies of insects, weeds, or other pests, or as crop pollinators.

3 Identification and Information Activities. Identification activities involve the efforts of taxonomic specialists who make hundreds of thousands of identifications annually for many Federal agencies, State organizations, and university researchers within the U.S. and in foreign countries. The following table indicates the number of identifications made by the scientists of the Systematic Entomology Laboratory during the past 10 years.

Year	No. of Identifications	Year	No. of Identifications
1964	69,136	1969	92,521
1965	72,612	1970	106,404
1966	77,129	1971	90,276
1967	91,899	1972	45,368
1968	101,494	1973	49,548
		1974	73,987

Such identifications, although primarily a service function, are essential to the research, control, and regulatory programs of ARS and many other agencies. In addition, identifications contribute to the overall objectives of taxonomic research in ARS by providing new information such as newly discovered species, new locations of known species, or new insights in combinations of species. Providing information on host relationships, distribution, biologies, etc., to other researchers is also a major function of taxonomists. Such authoritative identifications and information can be provided only by highly experienced researchers with access to the vast scientific literature in many languages (dating back to 1758) and to extensive reference collections.

4 Curatorial Activities. Broadly representative and authoritatively identified reference collections and the world taxonomic literature starting with 1758 are the major working tools for taxonomic research and identification. Four-fifths of the 23-million specimen National Collection of Insects situated at the Smithsonian Institution is managed and curated by SEL scientists.

B Visualized Technology

1 Morphological Taxonomy. This will involve discovery and application of new methods and major refinement of existing techniques for recognizing differences and similarities in anatomical structures correlated with taxonomic relationships of populations. This type of research is of a continuing nature due to the great diversity and large number of species involved. Certain techniques may be made effective and taxonomic problems solved within a year, others may require 10 years or more.

Especially important is taxonomic research leading to the accurate identification of immature insects and mites. Information on larval host preferences, behavior, and morphological characters, now known for less than 5% of North American insects, is necessary because immature forms are often the stage of economic importance. In 10 years, we should be able to provide various information on the immature stages of 15% of the immature stages.

With increasing efficiency in application of current morphological techniques and development of new methods, identifications based on these methods can be expected to increase in authoritativeness and turn-around-time by 50% over the next 10 years.

2 Biosystematics. This will involve research on behavioral and physiological characteristics as a means of recognizing and classifying insect and mite populations that are biologically distinctive yet too similar anatomically to permit initial differentiation of preserved specimens. Due to the large number of species which are nearly identical anatomically, this type of research involves solution of problems over an extended period covering two to five years or more for each problem. Turn-around-time for identifications is not expected to be shortened by these approaches but authoritativeness of classifications will differ by several orders of magnitude.

3 Identification and Information Activities.

a Identification of described (10%) and undescribed (90%) insects, mites and other arthropods for the research, control, and regulatory programs of Federal and State agencies and of U.S. and foreign individuals. This activity is continuous; specimens important to other laboratories and agencies are received, identified, and returned on a continuing basis as a vital service, especially to ARS, APHIS, and FS programs.

b Production of manuals and identification guides of at least 5 major groups which will enable other research scientists and nonspecialists to identify correctly insects and mites. This, too, is an ongoing activity which will be continuous considering the vast number of species of parasites, predators, and pest species involved.

c Provision of published and unpublished information on host-prey relationships, distribution, biology, etc., to a wide variety of users.

4 Curatorial Activities. Increase in the extent of holdings of groups of importance to U.S. agriculture (primarily by purchase of specialist collections) will improve identification as well as research capability. For example, purchase of the H. Townes collection of parasitic wasps (Ichneumonidae) would double USNM present holdings (quantitatively) and increase quality of the collection by 50%.

C Research Approaches

1 Morphological Taxonomy.

a Apply existing methodology (utilizing anatomical characteristics of adults and immature stages of insects, mites, and other arthropods) to provide an improved basis for identification and classification (NER, Beltsville, MD; Washington, D.C.).

b Develop use of scanning electron microscope to discover new anatomical characteristics and clarify previously used characteristics (NER, Beltsville, MD; Washington, D. C.; NCR, Columbia, MO).

c Utilize statistical treatment of taxonomic data (numerical taxonomy) as a tool in taxonomic research (NER, Beltsville, MD; Washington, D. C.).

d Develop computer storage of morphological characteristics as a method in taxonomic research (None).

e Develop computer storage and manipulation of collection data associated with specimens as a taxonomic research tool (None).

f Develop computerized catalogs of insects and other arthropods of the world to vastly improve efficiency of handling the immense number of scientific names involved in systematics (None).

2 Biosystematics.

a Determine the extent to which genetic mechanisms that maintain the integrity of insect and mite populations and control individual behavior can be identified and used in classification (NER, Beltsville, MD).

b Utilize differences in food preference, courtship, response to physical stimuli, and other behavioral traits to classify insects and mites more accurately (NER, Beltsville, MD; Washington, D.C.).

c Utilize physiological and biochemical differences among populations to classify insects and mites (NER, Beltsville, MD).

d Determine the effects of physical and biotic environmental factors upon the appearance and behavior of insects and mites (NER, Beltsville, MD).

e Identify anatomical characteristics which may be reliably correlated with and reflect significant differences in behavior of insect and mite populations (NER, Beltsville, MD).

f Develop computer modeling of physiological, genetic, and behavioral characteristics as a tool in classification research (None).

3 Identification and Information Activities.

a Utilize new anatomical characteristics of adult and immature insects and mites for identification purposes (NER, Beltsville, MD; Washington, D.C.).

b Apply biosystematic techniques to identification of populations not readily identified by conventional methods (None).

c Develop identification guides for the use of non-taxonomists (NER, Beltsville, MD; Washington, D.C.).

d Improve access to existing reference specimens by new computerized data handling systems and develop a reference collection to assist taxonomic scientists elsewhere to make identifications and to develop classification systems (NER, Beltsville, MD; Washington, D.C.).

e In cooperation with the Smithsonian Institution, maintain and develop literature resources (None).

4 Curatorial Activities.

a In cooperation with Smithsonian Institution, develop information on reference collections (of insect and mite groups of importance to USDA missions) to be able to obtain those essential resources (None).

D Consequences of Visualized Technology

1 Morphological Taxonomy.

a Will provide a more rapid, efficient, and economical means of organizing taxonomic information needed to classify insects and mites, thus making possible the identification of a great majority of the species.

b Will provide information on distribution, host-prey associations, and seasonal activity of hundreds of thousands of species of insects and mites.

c Will improve the ability of taxonomists and other scientists associated with universities, State Experiment Stations, and museums to identify promptly species of immediate concern to their research programs.

d Will serve as catalyst that will accelerate all agricultural, biological, and health sciences concerned with insects and mites.

e Will contribute to the eventual completion of the classification framework for all insects and mites.

2 Biosystematics.

a Will increase the precision with which closely related, morphologically similar species can be identified, and the degree to which genetic relationships at intraspecific levels can be established.

b Will enable revision of major classification systems of long and outmoded standing.

c Will increase the probability of successful use of beneficial organisms for control of pests, especially where host-specific biological control agents are concerned.

d Will improve the probability of genetic control of pest species through use of sexually compatible but genetically incompatible populations.

e Will contribute to improved methodology for the storage and retrieval of biological information relating to insects and mites.

3 Identification Activities.

a Will increase efficiency and effectiveness of Federal and State pest detection, control, and research programs.

b Will increase capability in finding and utilizing beneficial insects for biological control.

c Will provide data for ecosystem analysis and the eventual integration of diverse pest control systems.

d Will increase efficiency of response to requests by the public for identifications for research, control, esthetic, and other purposes.

e Will increase the effectiveness of all biological and ecological research which concerns insects and mites.

f Will contribute to improved methodology for the storage and retrieval of biological information relating to insects and mites.

4 Curatorial Activities.

a Improved and enlarged collections as a working tool will enable identification of species not now recognizable.

b Improved and enlarged collections, as a research resource, will provide more and higher quality raw material for research. Improvement in the kind and precision of taxonomic research data made possible by larger collections is equivalent to improvement in field studies made possible by more sophisticated and extensive sampling methods.

E Potential Benefits

1 Morphological Taxonomy. The benefits of this work will accrue from the degree to which research on the control, quarantine, behavior, etc., of insects and mites is hastened and made more effective. Taxonomic research eliminates the need for future workers to consult the scientific literature of the past 200 years and concurrently provides access, by accurate species identification, to the accumulated literature on control and bionomics. With the guidance of a taxonomic monograph, manual, or revision, supported by authoritatively identified specimens in a reference collection, an entomologist or other scientist with limited taxonomic training can more readily identify certain species of insects or mites of immediate concern in his research program. The value of such immediate identification may result in savings from a few man-hours to many thousands of dollars in the cost of a control program. For example, detailed information on the larval morphology and comparative biology of the Mediterranean fruit fly obtained through taxonomic research made possible the accurate identification of the first larva found in the Florida outbreak of 1956. This capability made it possible to initiate control measures within 24 hours after the discovery of this important pest species, thus avoiding the time required to rear the larvae to identifiable adults. Had the infestation been allowed to go unchecked during that time, the cost of eradication is estimated to have been 50% more than the approximately $12 million actually spent.

2 Biosystematics. The effects of biosystematic research have great potential in the field of biological control. According to one conservative estimate, 70% of all existing beneficial parasitic wasps are still species unknown to science, and biological information is unavailable for 97% of the species. Considering the fact that wasp parasites are believed to be the most effective and numerous of all insect biological control agents, the potential benefits in this field are tremendous.

Certain important species may be unrecognized because they are morphologically similar to already known species, and only biosystematic research will reveal their identities. Such sibling or cryptic species may be revealed as shown by the taxonomists' work with *Aphytis* spp. which include the most important wasp parasites of armored scale insects (citrus pests). Outstanding control was achieved in Florida and California after biosystematists distinguished between species of *Aphytis* so that they could be matched with susceptible host scale populations. As a result, several million dollars in insecticide costs have been saved, and energy savings have been possible. But, probably more important, the reduced use of insecticides has prevented outbreaks of other pest insects and mites.

3 Identification and Information Activities. During FY 1971-1975, inclusive, a total of 341,572 identifications were made by SEL at an average cost of $5.93. The benefits from this activity would require information from all those diverse Federal, State, and foreign agencies receiving the service which is not feasible logistically. The dollar benefits in terms of increased research effectiveness are obviously enormous, as pest control research and pest control applications are directly dependent on correct identifications.

4 Curatorial Activities. Improvement of the National Collection of Insects has benefit for ongoing research and identification activities but also will be essential for solution of future, as yet unidentified problems. Ideally, the Collection should contain authoritatively identified specimens of all World species. Such a goal is impossible to reach. We are now no closer than 10% of the goal, and at current rates will require 50 years to reach 50% of the goal.

F Research Effort

1 Current Level

	Year	Current Support SY's	Current Support Gross Dollars	Expanded Effort 5/ SY's (ARS Only)
ARS	FY76	28.8	845,500	40
SAES 1/, 3/	FY75	7.6	365,123	--
Other 2/	FY76	10.3	427,339	--
Total		46.7	1,637,962	40
Years required for ARS to achieve the Visualized Technology			4/	4/

1/ From CSRS printout 14NOV75
2/ APHIS, CSRS, partly from CSRS printout 14NOV75; non-Federal expenditures not available.
3/ Many projects do not clearly pertain to taxonomy or identification.
4/ Time estimate not feasible due to nature of research.
5/ Includes base and additional SY

2 Expanded Level

i Morphological Taxonomy.

a Taxonomic research on and identifications of the grasshoppers, crickets, cockroaches, and related insects are not now possible due to a vacant position which cannot be filled because of lack of funds. This important assignment cannot be ignored for many more months due to the obvious economic importance of these insects. (Orthoptera - 1 SY).

b The Lepidoptera (moths; 120,000 species) and Coleoptera (beetles; 280,000 species) are huge insect orders of prime economic importance. The small number of taxonomists now engaged in research on these groups, many species of which are not yet known to scinece, is inadequate to the needs of science. (Immature Lepidoptera - 1 SY; Adult Lepidoptera - 1 SY; Adult Coleoptera - 1 SY).

c One of the largest fly families, the Tachinidae, contains 8,000 species which parasitize some of our most economically important pest insects. The taxonomic specialist now covering part of this assignment will soon retire, but the family requires at least two specialists to meet the needs for taxonomic research in it. (Diptera (Tachinidae) - 1 SY).

d Highly accurate and detailed illustrations are required for efficient reporting of taxonomic research. Scientific papers can be shortened measurably by illustrating characteristics that otherwise must be described, usually less adequately, in words. (Scientific Illustrators - 3 MY).

e Due to widespread interest in spiders, their importance as generalized predators of pests and the actual medical importance of several species, there is need to initiate research on and perform identifications of several thousand specimens each year. Currently, spiders sent to the SEL are identified by a cooperating scientist, Dr. W. Peck, Central Missouri State College, Warrensburg. (Spider taxonomist - 1 SY).

f Paraprofessionals, including curatorial assistants, are needed to provide the indispensable working tool of a well-identified, well-arranged, and properly preserved reference collection without which taxonomic research is not possible. (Paraprofessional assistants - 10 MY).

g A corps of information specialists is needed to maintain and develop for research taxonomists one of their most important working tools - a well-organized and up-to-date library, reprint collection, and card catalog. The literature of systematic entomology is so vast and widely scattered that taxonomists cannot hope to cope with this problem alone. (Information specialists - 4 MY).

ii Biosystematics

a Many wasp parasites of agriculturally important pests have biological characteristics that distinguish the species, while they cannot be distinguished morphologically at all. To answer these research needs effectively, it is necessary to work across the order of parasitic wasps rather than in only a restricted number of families. (Hymenoptera - 1 SY).

b The aphids, white flies, and psyllids are an exceedingly difficult (taxonomically) group of agriculturally important insects. Because of the enormous amount of variation in these groups, including changes in appearance and behavior from one generation to the next, it is essential that biological and morphological studies be integrated to formulate a useful classification scheme. To solve the many problems in this area a biosystematist is needed to work out biological information. (Sternorrhyncha - 1 SY).

c Biosystematic research needs are not entirely predictable but we do know that all necessary biosystematics expertise cannot be found in SEL at current or likely future staff levels. Funds for Cooperative Agreements are needed to fill these gaps. Usual SEL salary: operating funds (95:5) are not adequate for this purpose. ($50,000 per year).

iii Identification, Information, and Other Service Activities.

a Paraprofessionals are needed to identify those insects and mites which are commonly submitted for identification, releasing SY time and effort to deal with research and identification problems at their own level of competence. (Paraprofessionals - 2 MY).

b Many insect species of potential importance to agriculture have not been described or illustrated adequately for positive identification. The precise identification of such species requires a great deal of knowledge about, and experience with, the insect groups to which they belong. Taxonomic specialists with wide acquaintance with these groups are needed to solve these important problems. (Hymenoptera - 1 SY), (Lepidoptera - 2 SY).

c Paraprofessionals are required to produce the basic information included in identification guides which can be used by non-taxonomists to identify pests of economic importance. (Paraprofessionals - 3 MY).

d Illustrations in color and black and white are the backbone of identification guides in explaining in a direct way those characteristics that words cannot describe. The SEL has only 1 part-time staff illustrator. (Illustrators - 3 MY).

iv Curatorial Activities

Major private collections are the primary source of collection improvement. Funds for purchase of one major collection per year are needed ($25,000).

Totals (ARS)	
SY	MY
11	25

Facility Addition/Renovation

Space not now available should be provided to accommodate all 3 major areas of systematics activity:

i Present space does not allow adequate working room for existing staff.

ii Staff expansion will require additional space for scientists, support staff, and working tools.

iii Additional space is required for expanding collections and library generated by research progress of existing staff.

Funding Required: $300,000

IV Principal Contributors

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NOTE: The expanded support level reflected in this National Research Program represents staff views as to the additional level of staffing that can be effectively used in meeting the long-term visualized objectives for this program. These do not reflect commitments on the part of the Agency.